Evolution of the boundary between the western and central Lachlan Orogen: implications for Tasmanide tectonics

Differences in oblique overprinting, along-strike complexity as well as structural, metamorphic and timing constraints suggest that the boundary between the western and central subprovinces of the Lachlan Orogen, currently designated by the Governor Fault, cannot be a single structure. Previously limited data on the nature and kinematics of the fault/shear systems defining the boundary have led to varying scenarios for the tectonic evolution of the Lachlan Orogen. These scenarios either involve large-scale strike-slip displacement along the boundary with subsequent overthrusting or convergence of oppositely vergent thrust-systems with limited strike-slip translation. Geometrical constraints, fabric chronology and kinematic indicators in both the Mt Wellington (Melbourne Zone) and Governor (Tabberabbera Zone) Fault Zones indicate that maximum displacements relate to thrusting and duplex formation, followed by minor strike-slip faulting perhaps in response to slightly oblique collision of the Melbourne and Tabberabbera structural zones. Collision of these zones took place between *ca* 400 and 390 Ma. At Howqua, structural relationships indicate that collision involved northeast-directed thrusting of the Melbourne Zone (Mt Wellington Fault Zone) over the Tabberabbera Zone (Governor Fault Zone), and was followed by regional, northwest-trending, open folding. These structures overprint the dominant fabrics and metamorphic assemblages that are interpreted to relate to disruption and underthrusting of Cambrian oceanic/arc crust during closure of a marginal basin. Major deformation in the Tabberabbera Zone took place from *ca* 445 Ma and was associated with mélange formation, underplating and imbrication or duplexing (Governor Fault Zone, East Howqua segment). At slightly higher crustal levels, and following deposition of Upper Ordovician black shale and chert sequences (*ca* 440 Ma), Tabberabbera Zone evolution included offscraping of a serpentinite body (Dolodrook segment) that may have been either a Marianas-style seamount or transform fault zone within the Cambrian oceanic/arc crust. Major thrusting in the Mt Wellington Fault Zone was underway sometime after *ca* 420 Ma, and in contrast to the Governor Fault Zone, no mélange or broken formation was produced, metamorphism was at slightly higher temperatures and deformation probably occurred under higher strain states.

KEY WORDS: fault zone evolution, Governor Fault Zone, Lachlan Orogen, Mt Wellington Fault Zone, tectonic boundary.

INTRODUCTION

The boundary between the western and central subprovinces of the Lachlan Orogen is a key element in tectonic models of Lachlan Orogen evolution (Figure 1) (Fergusson 1987; Glen 1992; Gray 1997; Foster *et al.* 1999; VandenBerg *et al.* 2000; Willman *et al.* 2002). It is defined by a major change in tectonic vergence from east- to northeast-directed in the Melbourne Zone and to southwest-directed in the Tabberabbera Zone (Fergusson 1987; Gray 1997). The eastern margin of the Melbourne Zone comprises the Mt Wellington Fault Zone and the western margin of the Tabberabbera Zone is defined as the Governor Fault Zone (Gray 1995; VandenBerg *et al.* 1995; Fergusson 1998). Cambrian ophiolitic and volcanic arc-related rocks occur as fault slices in the basal levels of both fault zones in association with variably deformed Ordovician–Silurian pelitic rocks (Figure 2) (Gray 1995; VandenBerg *et al.* 1995; Gray & Foster 1998).

Interpretations of the structural and kinematic evolution of this complex tectonic boundary and related tectonic setting range from large-scale, strike-slip displacement followed by thrusting in an intraplate setting (Willman *et al.* 2002), strike-slip translation of opposing fold and thrust belts in an intraplate, backarc setting (Fergusson 1987, 1998) to formation of opposing accretionary-style thrust-wedges in a predominantly oceanic setting during closure of a backarc or marginal basin (Gray & Foster 1998; Foster *et al.* 1999). These models, and the

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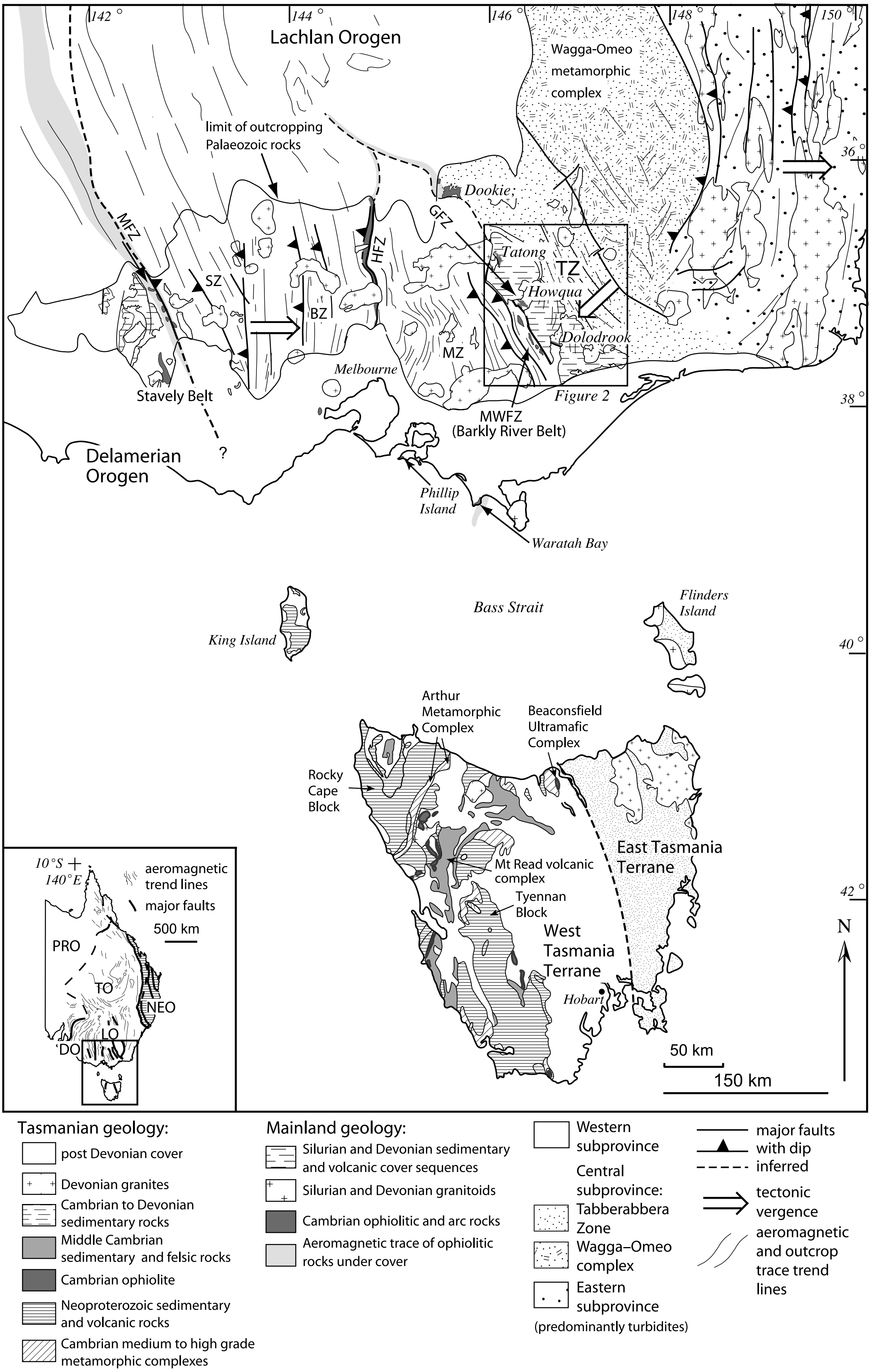


142°
144°
146°
148°
150
36°
38°
40°
42°
Lachlan Orogen
Wagga-Omeo metamorphic complex
limit of outcropping Palaeozoic rocks
Dookie
MFZ
SZ
BZ
HFZ
GFZ
Tatong
TZ
Howqua
Dolodrook
MZ
Melbourne
Figure 2
Stavely Belt
MWFZ (Barkly River Belt)
Delamerian Orogen
?
Phillip Island
Waratah Bay
Bass Strait
Flinders Island
King Island
Arthur Metamorphic Complex
Beaconsfield Ultramafic Complex
Rocky Cape Block
East Tasmania Terrane
Mt Read volcanic complex
Tyennan Block
West Tasmania Terrane
Hobart
N
50 km
150 km
10°S
140°E
aeromagnetic trend lines
major faults
500 km
PRO
TO
NEO
LO
DO
Tasmanian geology:
post Devonian cover
Devonian granites
Cambrian to Devonian sedimentary rocks
Middle Cambrian sedimentary and felsic rocks
Cambrian ophiolite
Neoproterozoic sedimentary and volcanic rocks
Cambrian medium to high grade metamorphic complexes
Mainland geology:
Silurian and Devonian sedimentary and volcanic cover sequences
Silurian and Devonian granitoids
Cambrian ophiolitic and arc rocks
Aeromagnetic trace of ophiolitic rocks under cover
Western subprovince
Central subprovince:
Tabberabbera Zone
Wagga–Omeo complex
Eastern subprovince
(predominantly turbidites)
major faults
with dip
inferred
tectonic vergence
aeromagnetic and outcrop trace trend lines

range of possibilities in between, have been difficult to reconcile partly because of incomplete structural mapping, unresolved issues such as the exact position of the boundary, the structural and metamorphic history of the fault zones on either side, the geometry of the zone boundaries, and an understanding of what the Cambrian 'greenstones' represent. The tectonic boundary between the western and central Lachlan Orogen is currently defined as the Governor Fault (VandenBerg *et al.* 1995, 2000), but along-strike complexities suggest that this boundary cannot be defined as a single structure. In this paper, we present detailed structural maps and profiles, metamorphic data and Ar/Ar data from the Mt Wellington and Governor Fault Zones to address these issues (see also the companion paper by Spaggiari *et al.* 2003a: full-size colour versions of the maps presented in these papers are given in Spaggiari 2003a). These data provide a basis with which to discuss the evolution of the two subprovince margins prior to amalgamation, the nature of collision between the two subprovinces, timing implications and tectonic setting. The time-scales used in this paper are outlined in Spaggiari *et al.* (2003a).

GEOLOGICAL BACKGROUND

The succession of Cambrian rocks that crop out in both the Mt Wellington Fault Zone and Governor Fault Zone make up what has traditionally been termed the Mt Wellington greenstone belt (Harris & Thomas 1954; Crawford 1988). The belt has a general northwest–southeast strike and an outcrop length of ~180 km (Figures 1, 2). Aeromagnetic imagery shows that the Cambrian rocks most likely continue northwest under cover and truncate the northern tip of the Heathcote Fault Zone (Figure 1) (Spaggiari 2002). The fault zones are unconformably overlain by weakly deformed, Upper Devonian volcanics and sedimentary rocks exposed in a series of *en échelon* basins (Figure 2) (Howitt Province: Marsden 1976). Tracing the position of the western and central Lachlan Orogen boundary therefore requires along-strike correlation of the intervening exposed segments of the Mt Wellington and Governor Fault Zones.

Although Crawford (1988) recognised distinct lithological differences in the Cambrian rocks in the belt, the structural relationships between these remained unclear. It is now recognised that Cambrian, calc-alkaline arc andesites (Barkly River Belt) are confined to the Mt Wellington Fault Zone of the Melbourne Zone, whereas Cambrian tholeiitic and boninitic mafic to ultramafic rocks are confined to the Governor Fault Zone of the Tabberabbera Zone (Figure 2) (VandenBerg *et al.* 1995; Fergusson 1998). Both sequences are Middle to Late Cambrian in age, and the tholeiitic and boninitic series have suprasubduction zone affinities (Crawford & Keays 1987; Spaggiari *et al.* in press). Given the similarity in age, the calc-alkaline sequence may represent the mature (or oceanic arc) stage of the suprasubduction zone system (e.g. Shervais 2001).

Melbourne Zone

The Melbourne Zone is bound to the west by the Heathcote Fault Zone and dominated by Silurian–Devonian quartz-rich turbidites (Figure 1). The Ordovician sedimentary sequence in the east of the zone is condensed and largely consists of Upper Ordovician black shale and siltstone (Mt Easton Shale), overlain by Silurian – Lower Devonian quartz-rich sandstone and siltstone (Jordan River Group: VandenBerg *et al.* 2000). Apart from the Mt Wellington Fault Zone, the Melbourne Zone is distinctly less deformed than adjacent structural zones, and is characterised by upright, open folding along northwest–southeast-trending axes. Fold interference patterns and curvilinear axial surface traces in the north are interpreted to relate to amalgamation of the Melbourne and Tabberabbera Zones in late Early to Middle Devonian times (Gray & Mortimer 1996). In the east, open folds gradually become tighter and axial surfaces become inclined to the southwest as the Mt Wellington Fault Zone is approached (VandenBerg *et al.* 1995; Gray & Mortimer 1996). These folds link into a ~20 km-wide zone of polydeformation comprising the Mt Easton Fault Zone and the Mt Wellington Fault Zone (Figure 2) (Gray 1995; VandenBerg *et al.* 1995).

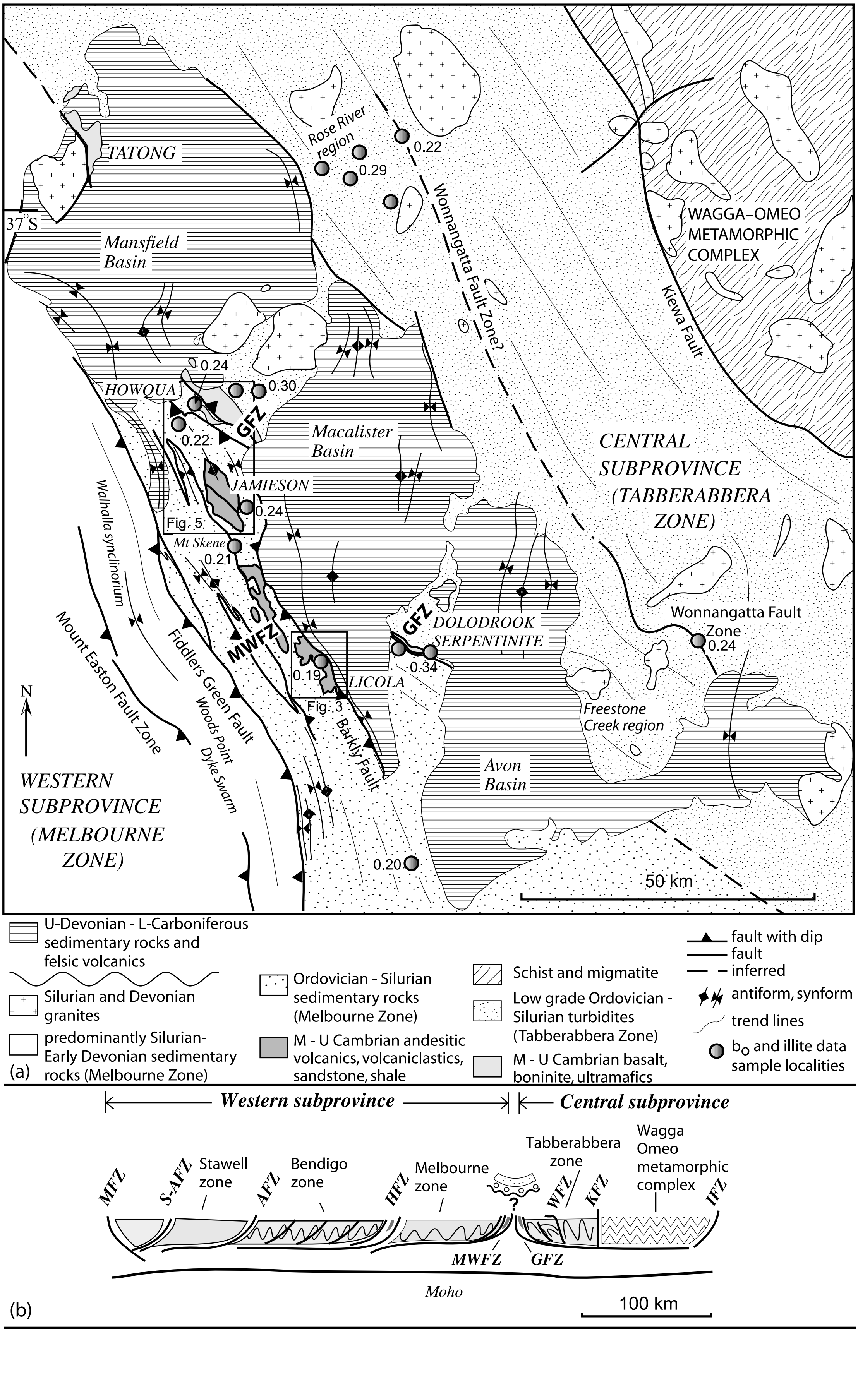
The nature of the basement to the Melbourne Zone has long been a contentious issue (Chappell *et al.* 1988; Fergusson & Coney 1992; Collins 1998; Gray & Foster 1998). The most recent interpretation is similar to the 'Victorian microcontinent' proposed by Scheibner (1985), now termed the Selwyn Block by Cayley *et al.* (2002). The Selwyn Block is inferred to be rigid basement of probable continental affinity, Neoproterozoic to Cambrian in age, and linked to similar rocks in Tasmania. The Heathcote Fault Zone and Governor Fault Zone are interpreted to override the block margins while the block acted as a rigid middle and lower crustal wedge, protecting overlying Melbourne Zone rocks from strong deformation (Cayley *et al.* 2002). However, it should be noted that no unequivocal outcrops of the block have been found and its existence is based on indirect evidence.

Tabberabbera Zone

The Tabberabbera Zone comprises a thick succession of Lower Ordovician to Silurian turbidites (Adaminaby, Bendoc and Cobbannah Groups) inferred to be underlain by the Cambrian (ophiolitic) marginal basin crust, as indicated by exposure of conformable Cambro-Ordovician basalt, chert and turbidite at Howqua (Fergusson 1998; Spaggiari *et al.* 2002b). The Tabberabbera Zone turbidites are linked to the east by a high-T/low-P metamorphic complex (Wagga Omeo Complex: Figures 1, 2) (Fergusson

Figure 1 Map of the Lachlan and eastern Delamerian Orogens showing major structural and lithotectonic elements, the western, central and eastern subprovinces, the northern margin of Tasmania, and the location of Figure 2. BZ, Bendigo Zone; GFZ, Governor Fault Zone; HFZ, Heathcote Fault Zone; MFZ, Moyston Fault Zone; MWFZ, Mt Wellington Fault Zone; MZ, Melbourne Zone; SZ, Stawell Zone; TZ, Tabberabbera Zone (modified from Gray & Foster 1998; Meffre *et al.* 2000). Inset is of eastern Australia showing orogenic belts of the Tasmanides. DO, Delamerian Orogen; LO, Lachlan Orogen; NEO, New England Orogen; PRO, Proterozoic crust; TO, Thomson Orogen.

1987, 1998; Morand 1990; Gray 1997). High-T metamorphism of the structurally thickened Ordovician turbidite pile in the Wagga–Omeo Zone occurred between *ca* 435 and 425 Ma, accompanied by granitoid intrusion (Collins &



Hobbs 2001 and references therein). This was followed by exhumation of the metamorphic complex during south-east-directed transport between *ca* 410 and 400 Ma (Morand & Gray 1991; Foster *et al.* 1999). The amount of combined wrench-thrust displacement during emplacement of the complex is unclear, but on the western boundary it is estimated to be <50 km (Kiewa–Kancoona fault system: Gray & Foster 1998).

Turbidites in the Tabberabbera Zone are dominated by southwest-vergent, inclined chevron folds cut by steeply dipping fault zones (Fergusson 1987; Watson & Gray 2001). The western margin is defined by the Governor Fault Zone, interpreted to be the leading edge of a thrust system that has an imbricate fan geometry (Figure 2b) (Gray & Foster 1998). Exposure of fault slivers of Cambrian ophiolitic rocks in the Governor Fault Zone indicate that maximum displacement has occurred at the front of this system. The Cambrian ophiolitic rocks are exposed in a series of structural highs at Dookie, Tatong, Howqua and Dolodrook (Figures 1, 2). In the southern part of the Tabberabbera Zone, Lower to Middle Ordovician Adaminaby Group turbidites in the east are separated from ?Upper Silurian Cobbannah Group turbidites in the west by the Wonanngatta Fault Zone, marked by an ~2 km-wide mélange zone (Figure 2) (Fergusson 1987, 1998). The main foliation in the fault zone has a predominant northeast dip, and kinematic indicators such as small-scale duplexes and rotated slivers of chert and silicified shale indicate top to the southwest thrusting. The chert contains a Tremadocian fauna that suggests that it is likely to be part of the same sequence that overlies Cambrian basalt exposed in the Governor Fault Zone at Howqua (Howqua Chert: Figure 2) (Stewart & Fergusson 1988).

Turbidites southwest of the Wonanngatta Fault Zone (Freestone Creek area: Figure 2) are folded into gently plunging, east-southeast-trending, open to tight folds with steeply northeast-dipping axial surfaces, indicative of southwest-directed tectonic transport. These are cut by Lower Devonian granitoids (Richards & Singleton 1981; Fergusson 1987). Turbidites east of the Wonanngatta Fault Zone are multiply deformed and have tight to isoclinal folds of similar orientations to those in the southwest (Fergusson 1987). Chevron folds in the northern Tabberabbera Zone are cut by faults associated with zones of broken formation (Watson & Gray 2001). These zones are interpreted to have formed initially in unconsolidated rocks and become intensely deformed as they were incorporated into the fault zones (Watson & Gray 2001).

Figure 2 (a) Map of the eastern Melbourne and Tabberabbera Zones (modified from VandenBerg *et al.* 1995, 2000; Gray & Foster 1998), showing locations of the Mt Wellington and Governor Fault Zones, Cambrian igneous associations, Upper Devonian cover sequences, Wagga–Omeo metamorphic complex, simplified structure and stratigraphy, illite crystallinity (IC) and b_o sample locations, and location of Figures 3 and 5. Average IC values for each location are shown: IC < 0.25 (epizone), 0.25 < IC < 0.42 (anchizone) (boundaries after Warr & Rice 1994). (b) Schematic crustal architecture profile at 37.5°S latitude illustrating thrust system geometry, and location and geometry of the collision zone between the Mt Wellington and Governor Fault Zones. AFZ, Avoca Fault Zone; IFZ, Indi Fault Zone (modified from Gray 1997); KFZ, Kiewa Fault Zone; S-AFZ, Stawell–Ararat Fault Zone; WFZ, Wonanngatta Fault Zone.

MT WELLINGTON FAULT ZONE

Licola and Fullarton segments

The Fullarton and Licola segments (Figure 3) consist of southwest-dipping fault slices of Cambrian calc-alkaline volcanics and volcaniclastics, and variably deformed, Ordovician–Silurian pelitic rocks. They are bound to the east by the Barkly Fault, a relatively late structure that juxtaposes the volcanic rocks over Upper Devonian rocks of the Macalister Basin (Figures 2, 3) (Harris & Thomas 1954). The pelitic rocks are linked to regional northwest-trending anticlinoria and synclinoria to the west (VandenBerg *et al.* 1995). The volcanic succession comprises Middle–Upper Cambrian andesite (Tobacco Creek Andesite, U–Pb age of 500 ± 8 Ma: Spaggiari *et al.* in press), andesitic volcaniclastics and volcanogenic sandstone (Table 1). The clastic rocks show minimal reworking and include olistoliths of recrystallised limestone, and lenses and clasts of pyritic black shale (Cob Spur Andesite Breccia). The overlying sedimentary sequence consists of Upper Ordovician black shale (Mt Easton Shale), and sandstone and siltstone of Silurian age (Jordan River Group: VandenBerg *et al.* 1995).

The structural architecture and geometry of the two segments is highlighted by an along-strike elevation increase of ~600 m from southeast to northwest (Figure 3). A single fault slice of the volcanic succession is inferred to cover the exposed eastern length of the Fullarton and Licola segments, bound to the east by the Barkly Fault (Figures 3, 4). A second fault slice of volcanic rocks occurs structurally above this in the Fullarton segment, and the fault contact is marked by a thin sliver of shale (Figures 3, 4 profile A–A′). The volcanic succession is variably deformed but dominated by a consistent southwest-dipping foliation that is particularly strong near, and subparallel to, major bounding faults (Table 1). Strongly deformed pelitic rocks overlie the lower volcanic fault slice, and are interpreted to form a tapered wedge between it and the overlying fault slice in the Fullarton segment. Less-deformed sandstone and siltstone form the structurally highest part of the sequence, in fault contact with both the volcanics and strongly deformed pelite (Figures 3, 4 profiles A–A′, D–D′). This relationship suggests that the pelite is a structural horse wedged between volcanic fault slices and structurally overlain by less-deformed sandstone and siltstone. Poor outcrop further west inhibits determination of repetition of the stacking order, but the presence of Cambrian volcanics to the north-west (VandenBerg *et al.* 1995) suggests this is likely.

The strongly deformed pelitic rocks in the wedge have a well-developed slaty cleavage defined by white mica and chlorite that is axial planar to mostly northwest-trending, tight to isoclinal folds (Table 1). These folds are refolded by similarly oriented, tight to isoclinal folds with a strong axial-planar crenulation cleavage defined by white mica and pressure-solution selvedges. Where intensely folded, the first foliation and bedding are transposed (see also

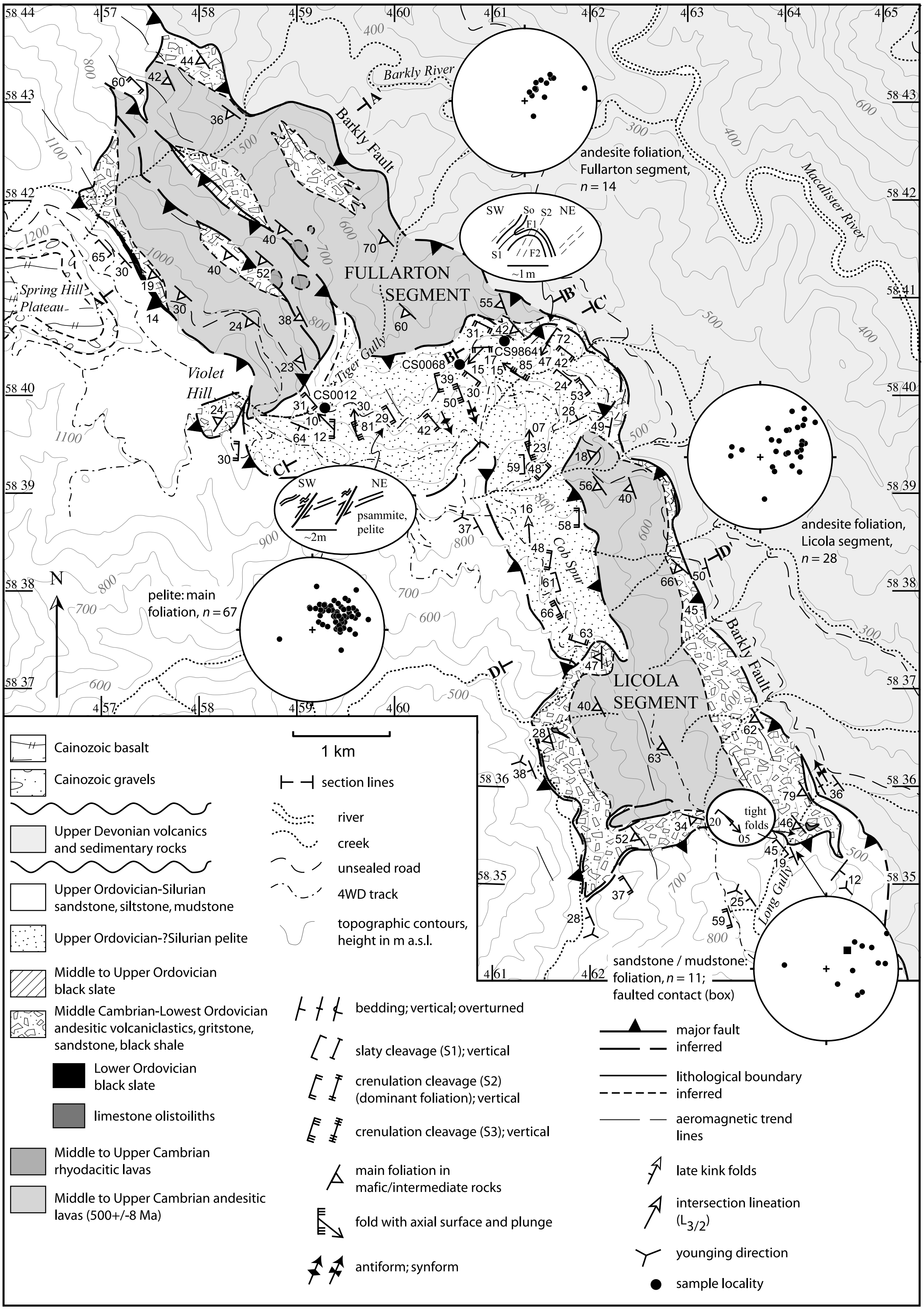


Figure 3 Geological map of the Licola and Fullarton segments of the Mt Wellington Fault Zone (modified from VandenBerg *et al.* 1995; Spaggiari 2002). See Figure 2 for location.

Gray & Foster 1998). Both foliations have a predominant southwest dip (Figures 3, 4). They are cut by small, southwest-dipping brittle faults and quartz veins, and folded by upright northwest-trending kink folds. Cooling columns in the andesite lavas show marked flattening with downdip elongation (e.g. at Wallaby Creek) and have average calculated strain states (X/Z) of 2.0:1 (Gray 1995). Limestone olistoliths are mostly completely recrystallised and on the southwestern margin of the Licola segment have an intense foliation axial planar to asymmetric folds. In contrast, overlying sandstone and siltstone in the structurally highest sequence are only weakly deformed (e.g. hangingwall of the fault contact at Long Gully: Figure 3).

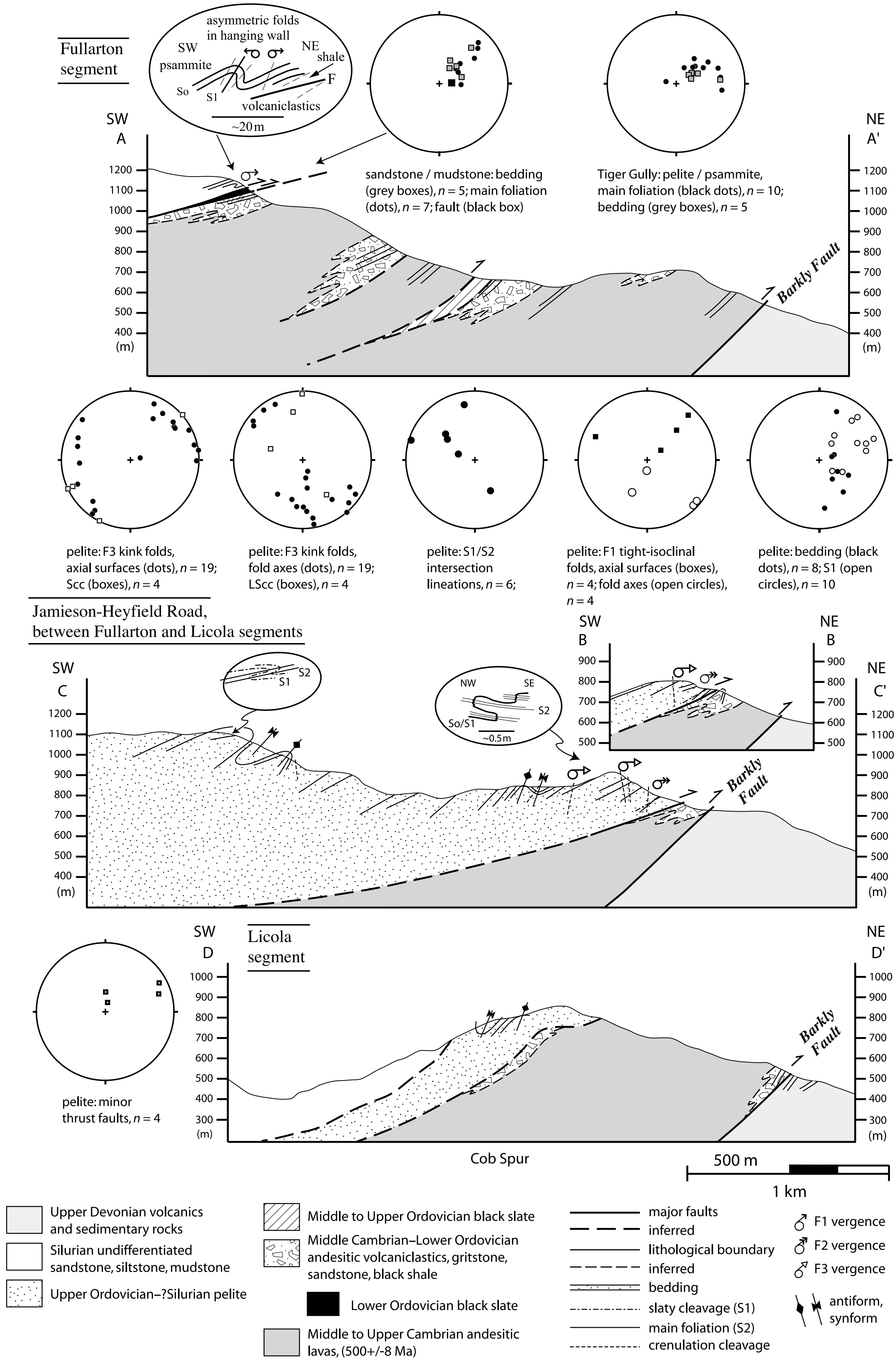
Jamieson segment

The Jamieson segment of the Mt Wellington Fault Zone comprises Cambrian andesitic to rhyodacitic or rhyolitic volcanics and volcaniclastics, and a cover sequence of black slate, chloritic slate and gritstone, pelite, sandstone and siltstone (Figures 5, 6) (Hendrickx 1993; VandenBerg *et al*. 1995). Calc-alkaline, andesitic volcanics dominate the northeastern part of the segment (Wrens Flat Andesite, Brissces Hut Andesite, Warrambat Andesite Breccia, Lakelands Flat Andesite Breccia), whereas the southwestern (and structurally higher) part is dominated by more felsic volcanics and volcaniclastics (Figure 5a, b) (Hardwicke Creek Rhyolite, Handford Creek Formation: VandenBerg *et al*. 1995). A northwest-trending fault separates the two lithological associations, which also appear to be internally imbricated (Figure 5b, profile E–E′). The main foliation in the volcanic succession has a moderate southwest dip, except on the eastern margin where it changes to a predominantly shallow northeast dip. Faulted contacts with the cover sequence have a similar geometry (Figure 5a, b). The main foliation (Figure 7a) is most pronounced in the volcaniclastics and is locally overprinted by a crenulation cleavage defined by rotated phyllosilicates and dark dissolution seams due to pressure solution.

Black slate and chloritic pelite in the hangingwalls of the faulted contacts on both sides of the volcanic succession have strong white mica ± chlorite slaty cleavages that are tightly to isoclinally folded. The early foliation is associated with growth of pressure shadows on pyrite grains and small lithics within gritty pelitic layers. On the eastern margin, the axial-planar fabric to the folds is also mostly defined by white mica but is also due to pressure solution. On the western margin (near Handford Creek track: Figure 5a, b, profile F–F′), tightly to isoclinally folded, veined black slates in the hangingwall of the fault contact above the volcanic succession have an axial-planar, transposition foliation that is indicative of high strain (Figure 7b). Fold-axis orientations of these folds vary from northwest trends to southwest plunges, coincident with decreasing interlimb angles (Figure 5b profile F–F′). Rodding in quartz veins and clast elongation in volcaniclastics in the footwall also have southwest plunges, thereby suggesting that folds in the hangingwall have been rotated into the stretching direction as they tightened. Some folds in the hangingwall slate show an asymmetry indicative of top to the northeast transport, as do curved pressure shadows on clasts in the volcaniclastics in the footwall. Total X/Z strain states calculated from quartz fibre lengths on pressure shadows on euhedral pyrite grains range from 4.0:1 in the hangingwall slates to 2.3:1 in the footwall volcaniclastics. These features are indicative

Table 1 Petrography of Mt Wellington Fault Zone rocks from the Licola and Fullarton segments.

Lithology	Primary lithology, mineralogy and textures	Metamorphic mineralogy and textures	Foliation(s)
Psammite/pelite	Quartz-rich, detrital muscovite, minor chlorite, plagioclase, metamorphic lithics	Minor white mica recrystallisation	Weak to moderate white mica foliation
Pelite (Tiger Gully to Cob Spur section)	Silty layers: quartz-rich, detrital muscovite, minor chlorite, plagioclase, metamorphic lithics	White mica and chlorite	Strong white mica and chlorite slaty cleavage; strong white mica and pressure solution crenulation cleavage (S_2); moderate white mica and pressure solution spaced crenulation cleavage (S_3)
Andesitic volcaniclastics, volcanogenic sandstone/siltstone, black shale	Clasts and lenses (mm scale to ~0.5 m, lenses tens of m long): andesite, black (pyritic) shale, quartz and chlorite-rich siltstone, chert, limestone; often crystal-rich: plagioclase, K-feldspar, pyroxene, quartz, chlorite; little or no reworking	Chlorite, albite, white mica, ±epidote ± quartz	Chlorite and white mica foliation, sometimes crenulated; cut by carbonate veins; Cataclasite often present near major faults
Limestone olistoliths	Calcite, shelly fragments	Mostly completely recrystallised	Strong calcite foliation, small asymmetric tight folds; some less deformed
Andesitic volanics	Hornblende-plagioclase, hornblende-clinopyroxene-plagioclase- or clinopyroxene-plagioclase-phyric; some aphyric lavas. Glass ± plagioclase matrix	Epidote, chlorite, albite ± titanite, actinolite rims on clinopyroxene and hornblende	Variably foliated: chlorite + albite ± epidote ± actinolite



Fullarton segment
asymmetric folds in hanging wall
SW
NE
psammite
shale
So
S1
F
volcaniclastics
~20m
SW
A
NE
A'
1200
1100
1000
900
800
700
600
500
400
(m)
sandstone / mudstone: bedding (grey boxes), n = 5; main foliation (dots), n = 7; fault (black box)
Tiger Gully: pelite / psammite, main foliation (black dots), n = 10; bedding (grey boxes), n = 5
Barkly Fault
pelite: F3 kink folds, axial surfaces (dots), n = 19; Scc (boxes), n = 4
pelite: F3 kink folds, fold axes (dots), n = 19; LScc (boxes), n = 4
pelite: S1/S2 intersection lineations, n = 6;
pelite: F1 tight-isoclinal folds, axial surfaces (boxes), n = 4; fold axes (open circles), n = 4
pelite: bedding (black dots), n = 8; S1 (open circles), n = 10
Jamieson-Heyfield Road, between Fullarton and Licola segments
SW
C
NE
C'
S2
S1
NW
SE
S2
So/S1
~0.5m
SW
B
NE
B
900
800
700
600
500
Barkly Fault
SW
D
NE
D'
Licola segment
1000
900
800
700
600
500
400
300
(m)
pelite: minor thrust faults, n = 4
Barkly Fault
Cob Spur
500 m
1 km
Upper Devonian volcanics and sedimentary rocks
Silurian undifferentiated sandstone, siltstone, mudstone
Upper Ordovician–?Silurian pelite
Middle to Upper Ordovician black slate
Middle Cambrian–Lower Ordovician andesitic volcaniclastics, gritstone, sandstone, black shale
Lower Ordovician black slate
Middle to Upper Cambrian andesitic lavas, (500+/-8 Ma)
major faults
inferred
lithological boundary
inferred
bedding
slaty cleavage (S1)
main foliation (S2)
crenulation cleavage
F1 vergence
F2 vergence
F3 vergence
antiform, synform

of thrusting of the cover sequence over the volcanic succession. Slate from the cover sequence has also been faulted within the volcanic succession, as indicated by a ~200 m-wide fault sliver of intensely deformed, veined black slate completely surrounded by volcanics near the southeastern margin. This most likely represents a structural horse within the imbricated volcanic succession (Figure 5b profile F–F′).

Mineral lineations and clast elongation along the western margin plunge consistently to the southwest but change to gentle northeast plunges on the eastern margin (Figure 5b). This indicates they are folded in the same manner as the fault contacts. The eastern margin is more structurally complex, where northeast- and southeast-plunging intersection lineations and fold axes are indicative of two fold sets at high angles. These have produced a domal fold interference pattern that is much less pronounced on the western side. The southeast-trending set relate to regional, open to tight folds that have folded the fault contact on the eastern side. Parasitic folds in slate and undifferentiated sandstone and siltstone in the northern part of the Jamieson segment (Mitchell's track: Figures 5, 6) are inclined to the southwest, as are northwest-trending kink folds throughout the segment (Figure 5b). Late warping along northeast-trending axes has contributed to the domal fold pattern and is the latest deformation to have affected the segment.

West Howqua segment

The West Howqua segment is the northern continuation of the Jamieson segment (Figures 5a, 6, 8) and comprises predominantly black slate interbedded with metasiltstone and minor psammite, and minor phyllite. Black slates are strongly deformed and crop out from an elevation of ~600 m at the northern margin of the Jamieson segment (near Mitchell's: Figure 5a) to over 1100 m along strike to the northwest (Slate Quarry site: Figures 5a, 8). Bedding and cleavage intersections in slate and metasiltstone indicate F1 folds plunge to the northwest along this section (Mitchell's track: Figures 5a, 6). At the highest structural levels (Slate Quarry site), the slates contain quartz veins boudinaged parallel to the main foliation and pressure shadows on framboidal pyrite grains indicative of strain states of (X/Z) up to 121:1. This, and the potential presence of underlying volcanics, suggest that the rocks exposed in the slate quarry may be part of another fault detachment (see also Gray 1995).

As in the other segments, the main foliation has a predominant southwest dip, and is axial planar to mesoscopic, F1 and F2 tight to isoclinal folds that plunge gently northwest or southeast (Figure 8). The foliations are defined by white mica and dark dissolution seams due to pressure solution, with the dominant mica growth in the first fabric. These foliations are folded by asymmetric (F3) kink folds with predominantly steeply northeast-dipping axial planes and mostly gentle plunges (Figure 8). There are no reliable younging indicators but these folds may be parasitic folds developed on the upper limb of an inclined antiform. As in the Jamieson segment, late warping of the fault zone along northeast-trending axes has produced doubly plunging (domal shaped) F3 folds.

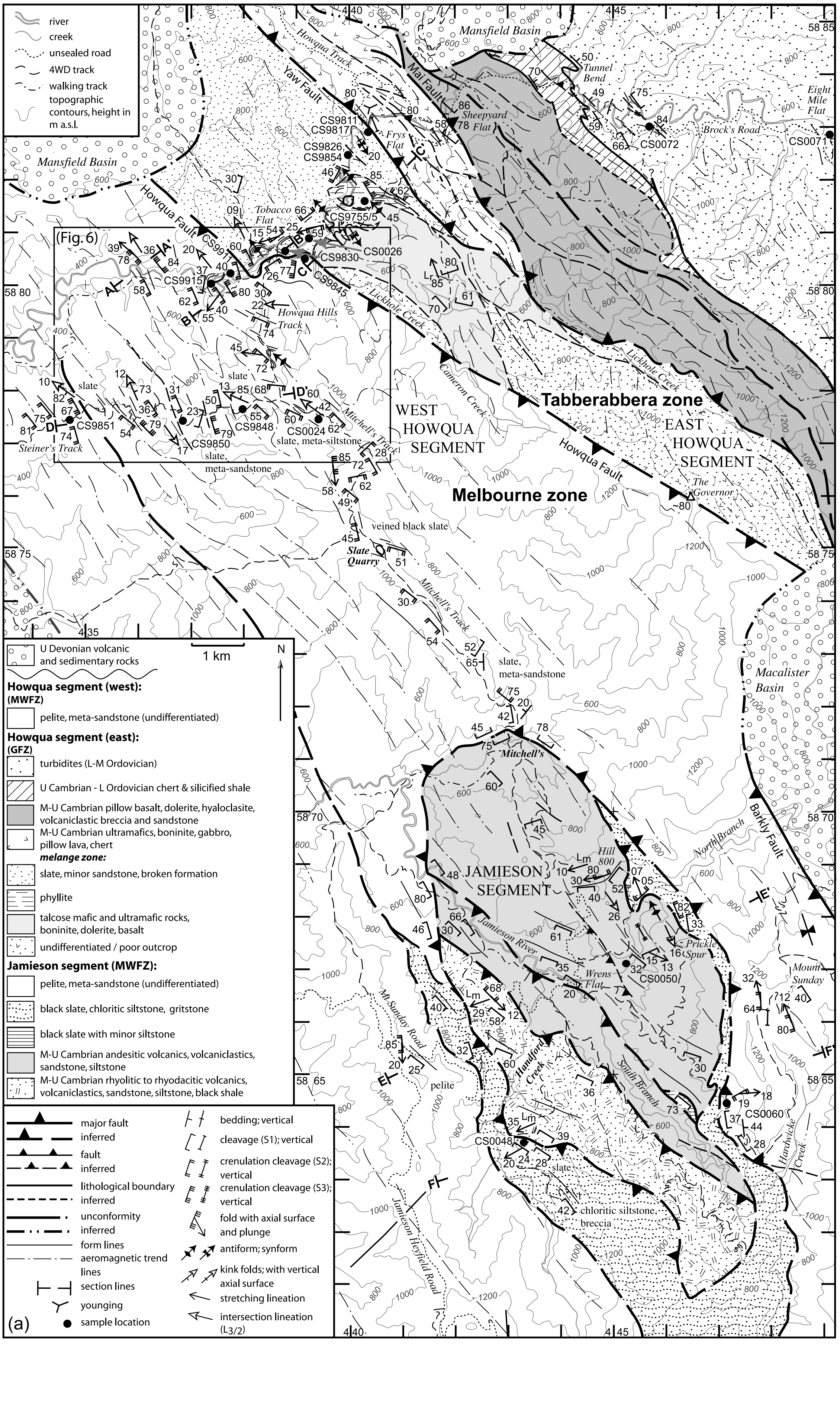
The eastern margin of the West Howqua segment of the Mt Wellington Fault Zone is bound by the southwest-dipping Howqua Fault. Phyllitic rocks exposed in the hangingwall (Howqua River section: Figures 6, 8) have a dominant southwest-dipping foliation cut by gently dipping shear bands indicative of top to the northeast thrusting. This predominant southwest dip is not present in mélange rocks of the Governor Fault Zone in the footwall of the Howqua Fault. The phyllitic rocks have a slaty cleavage that is folded into tight to isoclinal folds (F2) that have an axial-planar crenulation cleavage defined by white mica and marked dissolution seems due to pressure solution. Overprinting, regional, northwest-trending folds (F3) are traceable across the Howqua Fault, which is locally folded (Figures 6, 8). These folds are locally inclined to the southwest in the Mt Wellington Fault Zone and mostly upright in the Governor Fault Zone (Figures 6, 8).

Structural synthesis of the Mt Wellington Fault Zone

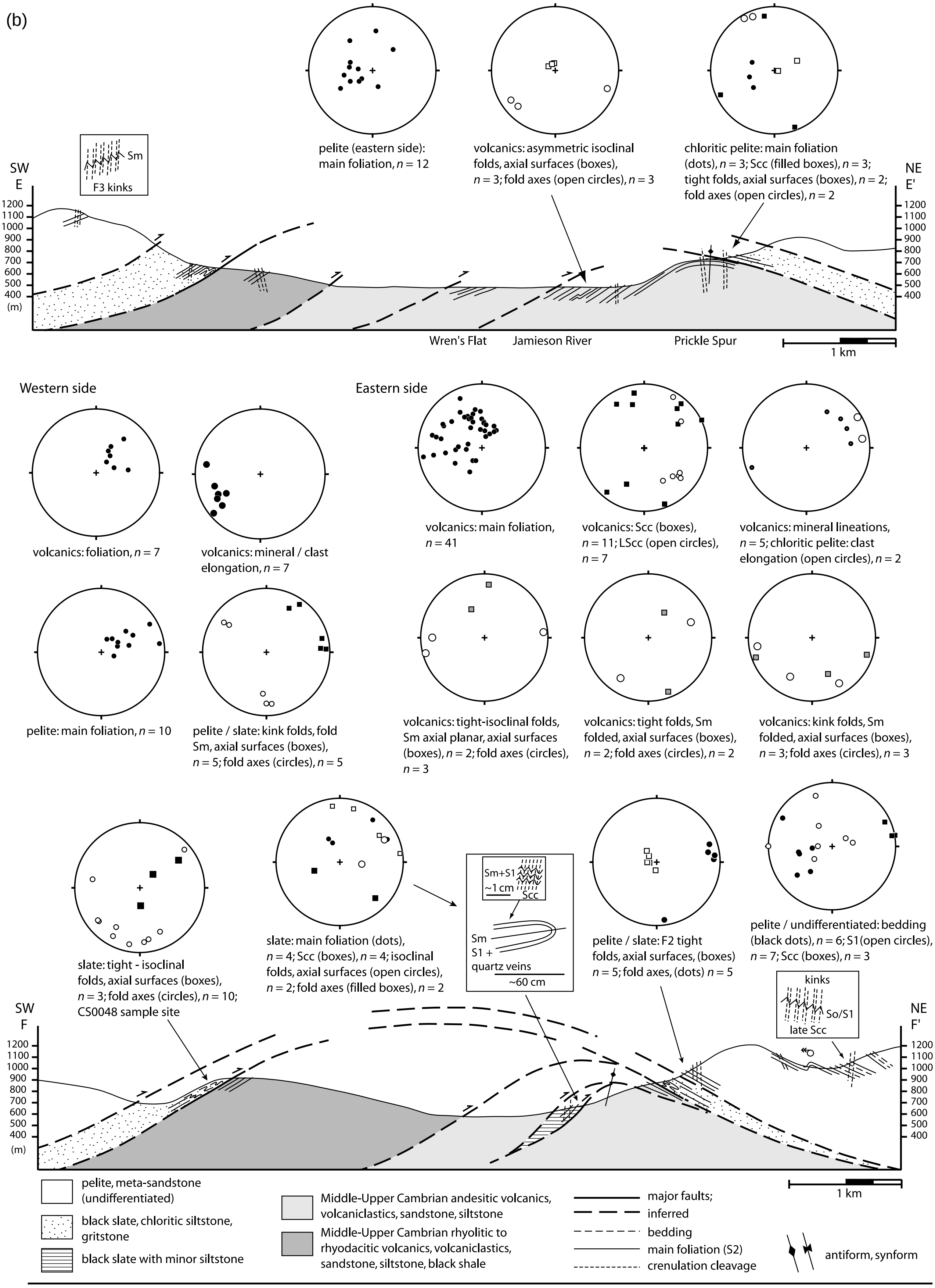
The occurrence of numerous fault slices of volcanics, high-strain zones in slate and pelite, and apparent repetition of stratigraphy can be interpreted to relate to duplexing of the Cambrian upper-arc stratigraphy and overlying sedimentary sequence (Figure 9). Unlike classic duplex models based on a well-known detailed stratigraphy, such as those described in Appalachian sections (Mitra 1988), duplex sequences in the Mt Wellington Fault Zone are difficult to reconstruct. This is partly due to restricted outcrop, but also because the stratigraphy is not always easy to define, particularly in the more strongly deformed rocks, because of the scarcity of fossils and a lack of distinct marker horizons. Furthermore, lithological associations suggest the initial sequence is unlikely to have had a 'layer-cake' morphology as it consisted of volcanic centres with flanking volcaniclastic debris flows, reef limestones, onlapping shale, local gritstone and depositional centres of sandstone, siltstone and mudstone. In this scenario, there may have been several small basins resulting in a complex stratigraphy. Irrespective of this, zones of high strain and polydeformation above fault slices of volcanics must correspond with structural breaks, and the volcanic sequence itself appears to be internally faulted (or imbricated). The are also few, if any, Cambrian plutonic rocks exposed, suggesting that only the upper part of the volcanic sequence was decoupled and imbricated. Exposure

Figure 4 Profiles and structural data from the Licola and Fullarton segments, Mt Wellington Fault Zone. See Figure 3 for section-line locations. All planes on stereonets are plotted as poles.

Figure 5 (a) Geological map of the Jamieson and Howqua segments of the Mt Wellington and Governor Fault Zones. The Howqua Fault marks the boundary between the Melbourne and Tabberabbera Zones in this region (modified in part from VandenBerg *et al*. 1995; Spaggiari 2002). See Figure 2 for location. (b) Profiles and structural data from the Jamieson segment, Mt Wellington Fault Zone. All planes on stereonets are plotted as poles.



river
creek
unsealed road
4WD track
walking track
topographic contours, height in m a.s.l.
Mansfield Basin
Macalister Basin
Howqua Fault
Yaw Fault
Mai Fault
Barkly Fault
Tabberabbera zone
Melbourne zone
WEST HOWQUA SEGMENT
EAST HOWQUA SEGMENT
JAMIESON SEGMENT
(Fig. 6)
Howqua Track
Tunnel Bend
Sheepyard Flat
Frys Flat
Tobacco Flat
Eight Mile Flat
Brock's Road
Howqua Hills Track
Lickhole Creek
Cameron Creek
Mitchell's Track
Steiner's Track
Slate Quarry
The Governor
Mitchell's
Hill 800
Jamieson River
Wrens Flat
Prickle Spur
North Branch
South Branch
Handford Creek
Hardwicke Creek
Mount Sunday
Mt Sunday Road
Jamieson Heyfield Road
slate
slate, meta-siltstone
slate, meta-sandstone
veined black slate
pelite
chloritic siltstone, breccia
CS9811
CS9817
CS9826
CS9854
CS9755/5
CS9911
CS9830
CS0026
CS9915
CS9845
CS9851
CS9850
CS9848
CS0024
CS0072
CS0071
CS0050
CS0060
CS0048
1 km
N
U Devonian volcanic and sedimentary rocks
Howqua segment (west):
(MWFZ)
pelite, meta-sandstone (undifferentiated)
Howqua segment (east):
(GFZ)
turbidites (L-M Ordovician)
U Cambrian - L Ordovician chert & silicified shale
M-U Cambrian pillow basalt, dolerite, hyaloclasite, volcaniclastic breccia and sandstone
M-U Cambrian ultramafics, boninite, gabbro, pillow lava, chert
melange zone:
slate, minor sandstone, broken formation
phyllite
talcose mafic and ultramafic rocks, boninite, dolerite, basalt
undifferentiated / poor outcrop
Jamieson segment (MWFZ):
pelite, meta-sandstone (undifferentiated)
black slate, chloritic siltstone, gritstone
black slate with minor siltstone
M-U Cambrian andesitic volcanics, volcaniclastics, sandstone, siltstone
M-U Cambrian rhyolitic to rhyodacitic volcanics, volcaniclastics, sandstone, siltstone, black shale
major fault
inferred
fault
inferred
lithological boundary
inferred
unconformity
inferred
form lines
aeromagnetic trend lines
section lines
younging
sample location
bedding; vertical
cleavage (S1); vertical
crenulation cleavage (S2); vertical
crenulation cleavage (S3); vertical
fold with axial surface and plunge
antiform; synform
kink folds; with vertical axial surface
stretching lineation
intersection lineation ($L_{3/2}$)
(a)



(b)
pelite (eastern side): main foliation, n = 12
volcanics: asymmetric isoclinal folds, axial surfaces (boxes), n = 3; fold axes (open circles), n = 3
chloritic pelite: main foliation (dots), n = 3; Scc (filled boxes), n = 3; tight folds, axial surfaces (boxes), n = 2; fold axes (open circles), n = 2
Sm
F3 kinks
SW
E
NE
E'
1200
1100
1000
900
800
700
600
500
400
(m)
Wren's Flat
Jamieson River
Prickle Spur
1 km
Western side
Eastern side
volcanics: foliation, n = 7
volcanics: mineral / clast elongation, n = 7
volcanics: main foliation, n = 41
volcanics: Scc (boxes), n = 11; LScc (open circles), n = 7
volcanics: mineral lineations, n = 5; chloritic pelite: clast elongation (open circles), n = 2
pelite: main foliation, n = 10
pelite / slate: kink folds, fold Sm, axial surfaces (boxes), n = 5; fold axes (circles), n = 5
volcanics: tight-isoclinal folds, Sm axial planar, axial surfaces (boxes), n = 2; fold axes (circles), n = 3
volcanics: tight folds, Sm folded, axial surfaces (boxes), n = 2; fold axes (circles), n = 2
volcanics: kink folds, Sm folded, axial surfaces (boxes), n = 3; fold axes (circles), n = 3
slate: tight - isoclinal folds, axial surfaces (boxes), n = 3; fold axes (circles), n = 10; CS0048 sample site
slate: main foliation (dots), n = 4; Scc (boxes), n = 4; isoclinal folds, axial surfaces (open circles), n = 2; fold axes (filled boxes), n = 2
Sm+S1
~1 cm
Scc
Sm
S1 + quartz veins
~60 cm
pelite / slate: F2 tight folds, axial surfaces, (boxes) n = 5; fold axes, (dots) n = 5
pelite / undifferentiated: bedding (black dots), n = 6; S1(open circles), n = 7; Scc (boxes), n = 3
kinks
So/S1
late Scc
SW
F
NE
F'
1200
1100
1000
900
800
700
600
500
400
(m)
1 km
pelite, meta-sandstone (undifferentiated)
black slate, chloritic siltstone, gritstone
black slate with minor siltstone
Middle-Upper Cambrian andesitic volcanics, volcaniclastics, sandstone, siltstone
Middle-Upper Cambrian rhyolitic to rhyodacitic volcanics, volcaniclastics, sandstone, siltstone, black shale
major faults;
inferred
bedding
main foliation (S2)
crenulation cleavage
antiform, synform

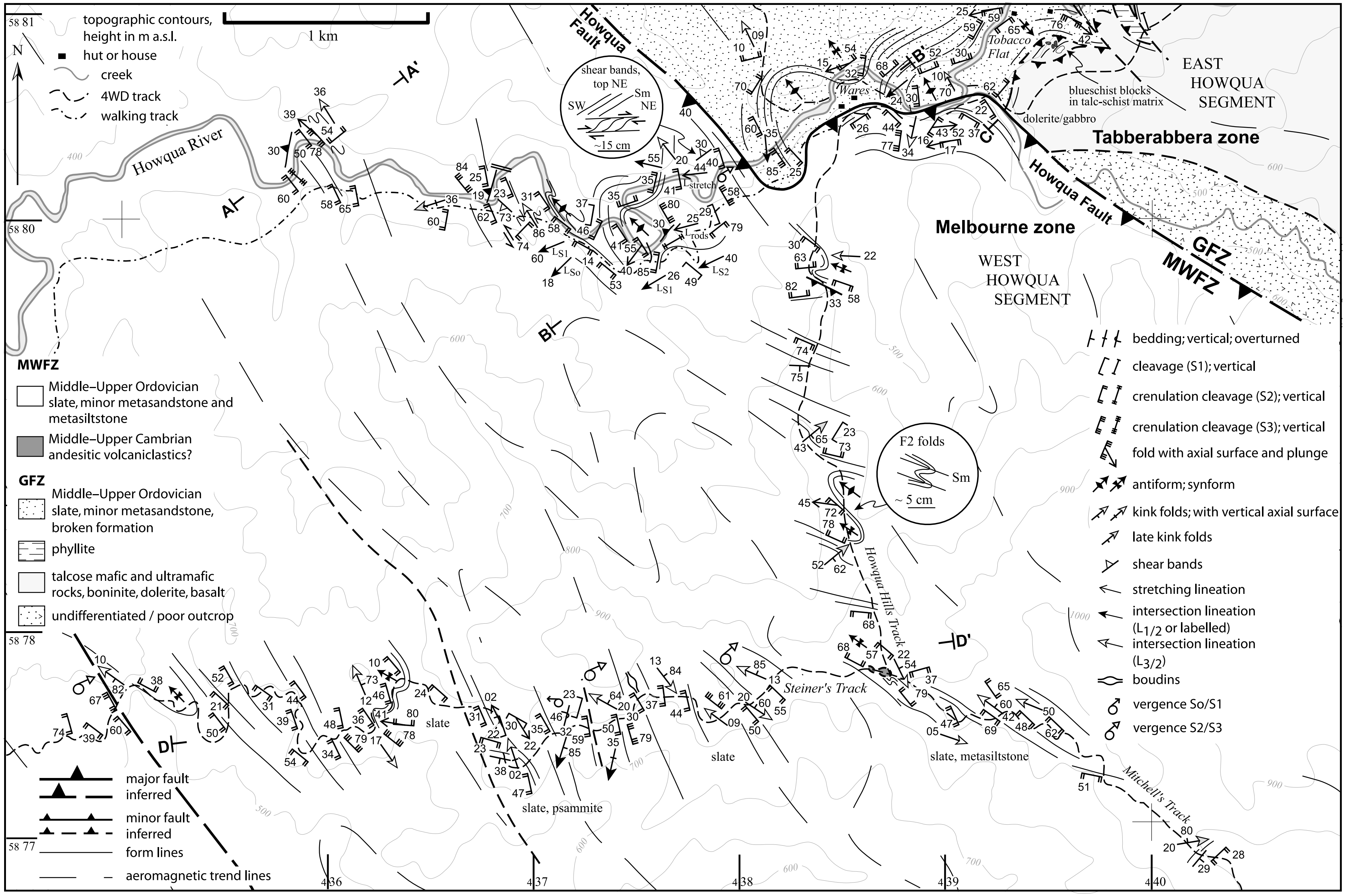


Figure 6 Detailed map of the West Howqua segment (Melbourne Zone) and part of the East Howqua segment (Tabberabbera Zone), showing the Steiner's Track and Howqua River sections. See Figure 5a for location.

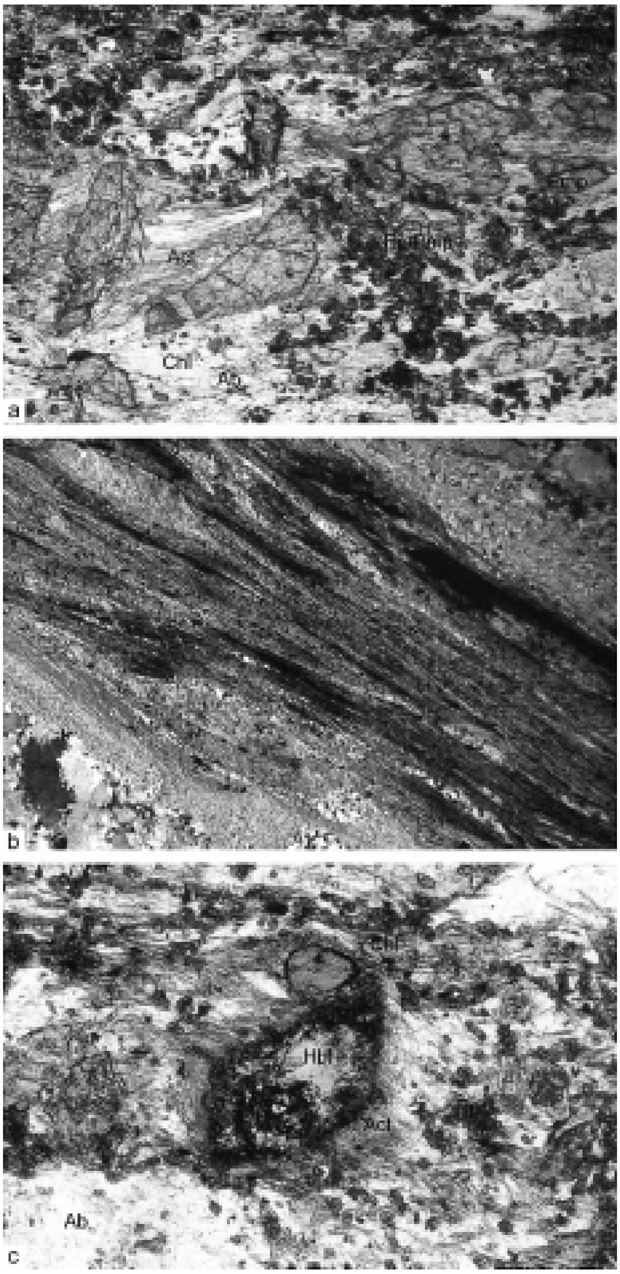


Figure 7 Photomicrographs from the Licola, Fullarton and Jamieson segments, Mt Wellington Fault Zone. (a) Volcaniclastic rock from the Jamieson segment, showing main foliation and pumpellyite–actinolite assemblage. Actinolite and chlorite rim relict grains and clasts, and fill pressure shadows. Relict plagioclase crystals are partially replaced by pumpellyite and epidote. Sample CS0050 (see Figure 5a for locality: Skene North 1:25 000 map sheet 8123–2-N: DU452670). Base of photomicrograph is ~3 mm. Plane-polarised light. (b) Strong mica fabric (top left to bottom right) in black slate from the thrust hangingwall, southwestern margin, Jamieson segment. Sample CS0048 (see Figure 5a, b for locality: Skene North 1:25 000 map sheet 8123–2-N: DU434637). Base of photomicrograph is ~3 mm. Crossed polarised light. (c) Hornblende andesite from the Licola segment, showing main foliation, greenschist assemblage, and actinolite needles rimming relict hornblende grains. Sample CS9761 (see Figure 3 for locality: Licola–Wellington 1:50 000 map sheet 8222-N: DU623392). Base of photomicrograph is ~3 mm. Plane-polarised light.

of the volcanic sequence at various topographic levels with polydeformed pelitic wedges (e.g. Licola and Fullarton segments) is interpreted to relate to duplexing of both the volcanics and overlying sedimentary sequence, and not just overthrusting of the cover as inferred by VandenBerg *et al*. (1995).

In simplified form, the main structural breaks are interpreted to be in three locations: (i) within the volcanic succession; (ii) within or at the top of overlying black slate; and (iii) within overlying pelitic rocks (Figure 9a). Duplexing of these layers would produce a stacking sequence of volcanics, slate and pelite (Figure 9b), but probably with considerable variation predominantly due to stratigraphic complexities such as variable thicknesses and local occurrence. This is suggested by the occurrence of thin slivers of black slate between volcanic slices (Jamieson and Fullarton segments), and the occurrence of pelite and very limited slate between the Fullarton and Licola segments. The occurrence of weakly deformed sandstone and mudstone in the hangingwall of the western margin of both the Licola and Fullarton segments (e.g. Long Gully: Figure 3) is in sharp contrast with highly strained rocks in the hangingwalls elsewhere (e.g. western margin, Jamieson segment), and may be indicative of out-of-sequence thrusting, bringing folded, stratigraphically and structurally higher cover rocks in fault contact with volcanics from the base of the pile. At the southeastern tip of the Licola segment (Figure 3), the sandstone and mudstone sequence appears to be folded over the tip of the duplex containing the volcanics, possibly in a manner similar to that of the sandstone and mudstone sequence that synformally flanks the eastern margin of the Jamieson segment (Figure 5a, b). There, the synform appears to pinch out along the Howqua Fault to the north. The geometry of the Howqua Fault at depth is difficult to constrain but it may have been part of an imbricate fan at the leading edge of a forward-propagating duplex system (Figure 9), and may also have been reactivated during the time the Barkly Fault was operative, that is, after deposition of the Upper Devonian basins.

GOVERNOR FAULT ZONE

East Howqua segment

Here, we summarise the geology of this segment, which is described in Spaggiari *et al*. (2002a, b; 2003b). At Howqua, the Governor Fault Zone comprises Cambrian ophiolitic rocks preserved as elongated, northwest-trending fault slices, and as blocks and smaller fault slices in mélange. The structural architecture from upper to lower levels consists of folded and faulted turbidites (Adaminaby Group: Fergusson 1998), folded bedded cherts and silicified shale (Howqua Chert), imbricated tholeiitic pillow basalt, dolerite, gabbro, volcaniclastics and chert, and imbricated mafic and ultramafic rocks including boninite (Lickhole Volcanics; 'Howqua Hills belt'). These overlie a ~2.5 km-wide mélange zone (which includes the 'Tobacco Flat belt') that forms the footwall to the Howqua Fault. Metamorphic pressure and temperature estimates, and deformation intensity increase downwards in this structural architecture without significant gaps across faults (Spaggiari *et al*. 2002a). Pillow lavas throughout the imbricated ophiolitic sequence indicate a consistent northeast-younging direction. The northeast-dipping contact between the basalt and chert is conformable along the Howqua River section, but may be faulted to the southeast where turbidite directly overlies pillow basalt with interbedded chert. An alternative explanation may be that the chert sequence thins to the southeast.

The mélange zone comprises blocks and slices of predominantly basalt, dolerite and boninite, some of which are enveloped in talc-schist matrix and metamorphosed up to blueschist conditions. These are interleaved with slate

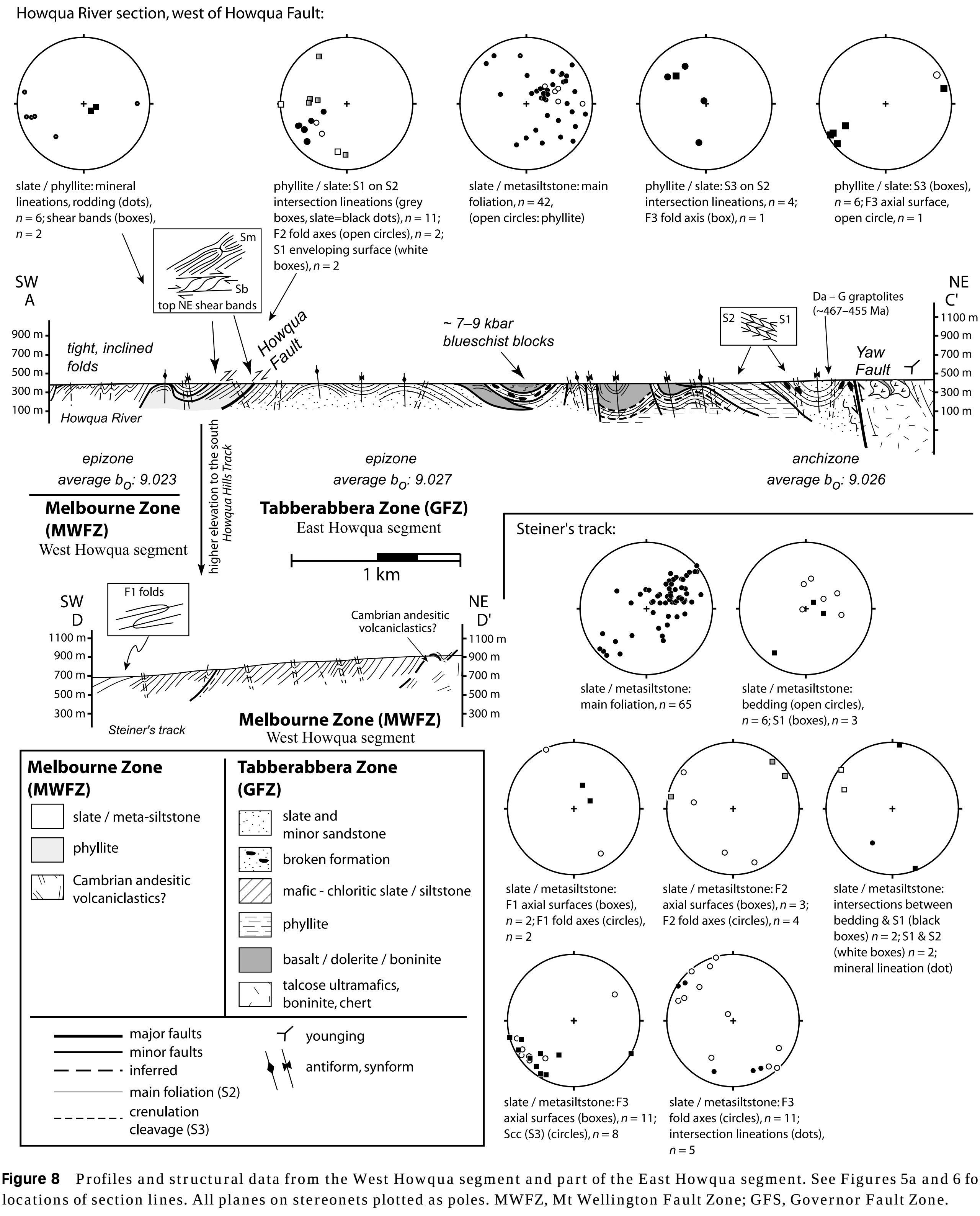


Figure 8 Profiles and structural data from the West Howqua segment and part of the East Howqua segment. See Figures 5a and 6 for locations of section lines. All planes on stereonets plotted as poles. MWFZ, Mt Wellington Fault Zone; GFS, Governor Fault Zone.

and phyllite that contain zones of stratal disruption (broken formation). The main foliation in the slate and phyllite is a crenulation cleavage that is axial planar to tight to isoclinal, predominantly southwest-plunging folds. This foliation has been dated at 446 ± 2 Ma (Spaggiari *et al.* 2002b). Unlike slate and phyllite in the Mt Wellington Fault Zone, this second foliation has a higher proportion of mica growth than the first foliation, which is predominantly due to pressure solution. The first foliation is interpreted to be associated with tectonic stratal disruption and initial formation of the mélange, while the crenulation cleavage relates to folding interpreted to have occurred during underplating of the mélange (Spaggiari *et al.* 2002a; 2003b). A third foliation is locally developed, and is axial planar to upright, open folds. These folds are interpreted to be the same set (F3) as the regional northwest-trending folds described in the Mt Wellington Fault Zone.

Tatong segment

The Tatong segment appears to be a northwestern extension of the East Howqua segment, but fault relationships between the Governor Fault Zone and Mt Wellington Fault Zone in this region remain obscure due to poor exposure (Figure 2). The sequence consists of Cambrian tholeiitic basalt, dolerite, minor gabbro, chert and silicified shale, and Ordovician turbidite (Crawford 1988; Brown 1998; VandenBerg *et al.* 2000). These rocks are almost completely surrounded by Upper Devonian rocks of the Mansfield Basin (Howitt province) with either faulted or unconformable contacts. The segment is difficult to interpret structurally and appears to have been significantly disrupted by formation of the Howitt province, but aeromagnetic imagery indicates that most of the Cambrian sequence dips to the northeast along its western margin (Spaggiari 2002; Spaggiari *et al.* in press). The eastern part of the segment is dominated by tholeiitic basalt with interbedded chert, similar to that of the East Howqua segment. Doleritic rocks in the western part have weakly developed, blue-green amphiboles that may be indicative of incipient blueschist–greenschist transitional assemblages. These occur next to strongly deformed, veined black slates. These features suggest that a similar sequence to that at Howqua may be present, that is, tholeiitic basalts possibly underlain by mélange.

Dookie segment

The Dookie segment (Figure 1) occurs northwest of the Tatong segment and coincides with a zone of approximately east- and northwest-trending magnetic highs. The Cambrian sequence is dominated by tholeiitic basalt, dolerite and gabbro, associated with volcanogenic sandstone, conglomerate, tuff and chert (Crawford 1988; Tickell 1989). The gabbro has a U–Pb (zircon) magmatic crystallisation age of 501.0 ± 0.7 Ma (Spaggiari *et al.* in press). The mafic rocks have metamorphic assemblages indicative of prehnite–pumpellyite or greenschist facies and show significant hydrothermal alteration with widespread epidote, calcite, quartz, (± axinite) veins. Unlike the rest of the Governor Fault Zone, this segment is not overlain or disrupted by the Upper Devonian Howitt province.

Most of the Dookie segment is under Quaternary cover but aeromagnetic data indicate it continues to the northwest (Figure 1). The data indicate that the east-trending section of the Dookie segment is flanked by northwest-trending, predominantly northeast-dipping Cambrian rocks (Spaggiari 2002). A strong high to the southeast coincides with sporadic outcrops of chert and basalt (Tickell 1989), and is subparallel to weaker highs further southeast, but these do not form a continuous link as far as the Tatong segment. In the central part of the Dookie segment, the Cambrian sequence is bound to the south by the north-dipping Dookie Fault (Tickell 1989). Cambrian basalts are in sharp fault contact, partly with Lower and Middle Ordovician turbidites and also with Silurian–Devonian turbidites of the Melbourne Zone (Gray & Mortimer 1996). The older turbidites also overlie and are in fault contact with the younger sequence. Turbidites in the immediate footwall of the Dookie Fault have northeast-

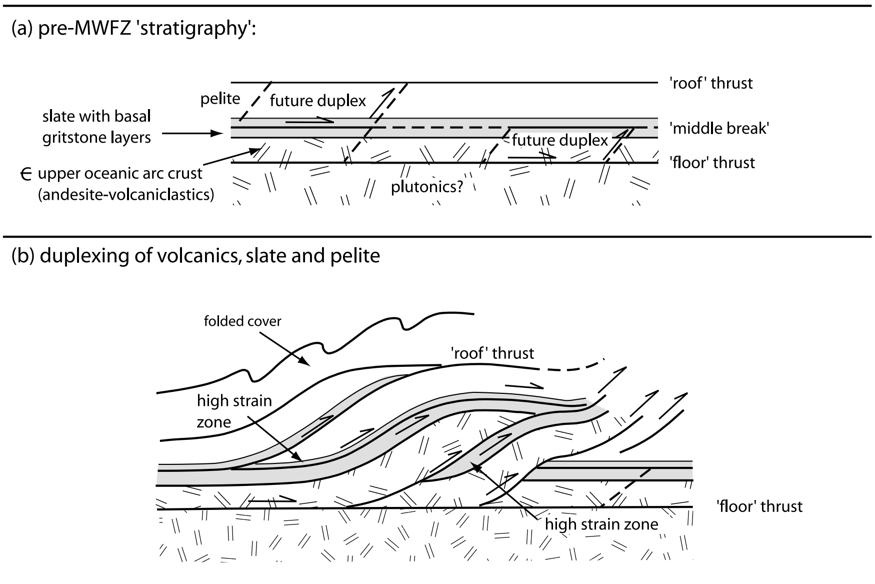


Figure 9 Schematic diagrams illustrating possible duplex geometry and detachment horizons in the Mt Wellington Fault Zone (MWFZ). (a) Interpreted locations of main structural breaks in a simplified pre-faulting stratigraphy. (b) Interpreted and simplified stacking order and geometry of the duplex system.

plunging folds cut by numerous brittle splays off the main fault. The hangingwall basalts are heterogeneously foliated and show marked epidote alteration. The foliation is cut by shear bands indicative of north over south displacement and north- and northeast-dipping brittle faults with downdip slickenside striae (Gray & Mortimer 1996).

Dolodrook segment

The Dolodrook segment is situated to the southeast of the East Howqua segment, with the intervening geology completely obscured by the Upper Devonian Macalister basin (Figure 2). This segment is fully described in Spaggiari *et al*. (2003) and Spaggiari *et al*. (2003b).

METAMORPHISM

Mafic–intermediate rocks

MT WELLINGTON FAULT ZONE

Volcanic rocks from the Mt Wellington Fault Zone have mineralogies consistent with either pumpellyite–actinolite or lower greenschist facies conditions. In the Jamieson segment, the volcaniclastics have a strong foliation defined by white mica, epidote, pumpellyite, chlorite, actinolite, albite and quartz, indicative of pumpellyite–actinolite facies. This mineralogy suggests the foliation formed between approximately 300–400°C and 200–700 MPa (Schiffman & Day 1999; Spaggiari *et al*. 2002a figure 12). Actinolite rims on hornblende and pyroxene in andesitic rocks in the Licola and Fullarton segments (Table 1; Figure 7c) are indicative of lower greenschist facies conditions.

GOVERNOR FAULT ZONE

Estimated metamorphic conditions of mafic rocks from the Governor Fault Zone, East Howqua segment, range from prehnite–pumpellyite at higher structural levels to greenschist and blueschist facies at lower structural levels (Spaggiari *et al*. 2002a). Small pods of volcanics with incipient blueschist to greenschist mineralogies occur in ultramafics in the footwall of Mai Fault, just above the mélange zone. In the Dookie and Tatong segments, mafic rocks also have assemblages indicative of prehnite–pumpellyite to lower greenschist conditions. Bluish amphiboles at Tatong may also be indicative of slightly higher P rocks in the western part of the segment. In the Dolodrook segment, the apparent lack of antigorite and minimal growth of talc in serpentinite, and the lack of actinolite in the pillow basalt sliver, are suggestive of metamorphic conditions perhaps no higher than prehnite–pumpellyite facies (Spaggiari *et al*. 2003a table 1).

Illite crystallinity and b_o values

TECHNIQUES: B_O CELL PARAMETER OF WHITE MICA

X-ray diffraction traces have been obtained from –2 μm fractions, separated from powdered slate samples. These fractions are tamped sideways into an aluminium cavity-mount made specially for mica b_o determinations. In addition, where large slate samples have been available, these have been ground flat at 90° to the cleavage and the sample plate placed directly into the diffractometer. All determinations have been made with a Siemens D500 diffractometer using the (211) peak of quartz as an internal standard. Instrument conditions were: Fe-filtered CoK_α radiation, 40 kV/25 mA, step scan 0.02°2θ from 70° to 75°2θ at 0.25°2θ/min. Divergence and scatter slits were 1° and a receiving slit of 0.05°. The b_o spacing was determined from a digital trace after computer stripping of the $CoK_{\alpha 2}$ contribution. Detailed discussions of the method and its application as a geobarometer of low-grade metamorphic rocks are found in Sassi and Scolari (1974) and Padan *et al*. (1982).

ILLITE CRYSTALLINITY DETERMINATIONS

The technique used follows the recommendations of Kisch (1991). In addition, computed illite crystallinity values have been obtained from digitised traces. Duplicate sedimented mounts have been prepared from –2 μm fractions of powdered slate samples, determinations have been made on air-dried and glycolated mounts. Specific instrumental conditions are: Siemens D501 diffractometer, Ni-filtered CuK_α radiation, 40 kV/30 mA, 1° divergence and scatter slits, 0.05° receiving slit, scans from 7.0° to 10.0°2θ at 0.5°2θ/min. Chart paper determinations were made from traces obtained with a time constant of 1 s and a chart speed of 2 cm/min. Calibration of these results has been carried out using a set of secondary polished slate standards (kindly supplied by H. Kisch of Ben-Gurion University of the Negev). The calibration correction obtained using these standards is insignificant, but it is noted that the equivalent Kübler peak widths (Kisch 1990), tend to be 0.03–0.04° Δ2θ broader than the half-widths supplied by Kisch (note supplied with standards). Smectite clays and paragonite, which can interfere with the (001) mica peak half-width determination, were not detected in the samples.

RESULTS

The illite crystallinity (IC) and b_o values presented here (Table 2; Figures 2, 10) are indicative of anchizonal to epizonal (prehnite–pumpellyite to greenschist) temperatures and intermediate pressure conditions (~400 MPa: Guidotti & Sassi 1986), respectively. In general, the data are similar to values for the Stawell and Bendigo Zones (western Lachlan Orogen) given in Offler *et al*. (1998), with perhaps slightly lower b_o values, particularly for the Mt Wellington Fault Zone. Variations in the IC data are consistent with the observed degree of white mica recrystallisation in the foliations, and the metamorphic mineralogy of the associated mafic and intermediate rocks.

Samples from within the fault zones generally have lower IC values (i.e. higher grade) than samples away from fault zones, although there is some potential bias in that the majority of samples come from within fault zones. Nevertheless, this is where foliation development by white mica recrystallisation is predominant in the Tabberabbera Zone. The exception is the Dolodrook segment, which shows anchizonal to diagenetic conditions. The IC values from the Mt Wellington Fault Zone are all indicative of epizonal conditions. The IC values from the Governor Fault Zone are indicative of anchizonal to mostly epizonal conditions, and diagenetic conditions occur in turbidites from the highest structural levels at Howqua (e.g. 8-mile Flat and further east: Figure 5a). Epizonal conditions are also indicated for the Wonanngatta Fault Zone, including the potential northern extension (Watson & Gray 2001), in contrast to anchizonal conditions away from the fault zone.

The b_o data are more difficult to interpret and only show minimal variation. The main differences are that Mt Wellington Fault Zone values are slightly lower than those from the Tabberabbera Zone (Figure 10). There is some indication that values from within the fault zones in the Tabberabbera Zone are generally higher than those from outside, but more data are needed to confirm this. Overall, there is nothing to suggest particularly large vertical displacements across faults. The b_o data suggest that significant erosion occurred prior to formation of the Upper Devonian basins, perhaps in the order of approximately 10 km or so. This is consistent with the change from marine to continental sedimentation, as recorded by redbed deposition in the Howitt province (Marsden 1976).

Table 2 Illite crystallinity (IC) and b_o data from the Tabberabbera Zone and Melbourne Zone (Mt Wellington Fault Zone).

Sample	Location	Map coordinates	b_o	IC
Tabberabbera Zone				
CS0007	Dolodrook River, southwest	(A) DU 749424	9.018	0.30
CS0010	Dolodrook River, southeast	(A) DU 778418	9.020	0.38
Wonangatta Fault Zone				
CS0062	Lower Dargo Road (0.5 km from CS0066)		9.030	0.22
CS0063	Lower Dargo Road (0.5 km from CS0066)		9.030, 9.030 s	0.26
CS0064	Lower Dargo Road (0.5 km from CS0066)		9.030	0.23
CS0065	Lower Dargo Road (0.5 km from CS0066)		9.024	0.26
CS0066	Lower Dargo Road (0.5 km from CS0062 – CS0065)	S37 32.288 E147 16.397	9.012 (weak peaks)	0.21
Rose River region				
CS0073	Near Whitfield, Rose River Road.	S36 50.366 E146 29.763	9.030	0.30
CS0074	Near Whitfield / Rose River	(E) DV 623239	9.024	0.26
CS0075	Rose River, (end of transmission line)	(E) DV 627241	9.030	0.26
CS0078	Rose River / Rose River Road.	S36 51.961 E146 33.467	9.020	0.32
Buffalo River region				
CS0076	Abbeyard Road., Buffalo River	S36 51.517 E146 40.826	9.018, 9.018 s	0.30
CS0077	Osbornes Bridge, Buffalo River	S36 40.904 E146 40.595	9.018	0.22
Upper Howqua River region				
CS0070	Upper Howqua River/8-mile Gap	(B) DU 500791	9.018	0.34
CS0071	Upper Howqua River/8-mile Flat	(B) DU 494828	9.018	0.34
CS0072	vpper Howqua River/unamed fault	(B) DU 457829	9.022	0.23
Governor Fault Zone				
CS9811	Howqua River, Frys Flat	(B) DU 403829	9.028	0.30
CS9826	Howqua River, Maxwells Huts	(B) DU 401826	9.022	0.23
CS9755.5	Howqua, near Whisky Flat	(B) DU 406816	9.023	0.23
CS9830	Howqua, Tobacco Flat	(B) DU 388807	9.037	0.23
CS9854	Howqua River, near Maxwell's Huts	(B) DU 400825	9.028	0.26
CS0026	Howqua River, Tobacco Flat	(B) DU 393811	9.024	0.22
CS9817	Howqua River, Fry's Flat	(B) DU 403829	9.023	0.28
Melbourne Zone (Mt Wellington Fault Zone)				
CS0067	Licola Road, Glenmaggie	S37 48.865 E146 40.220	9.026, 9.030 s	0.20
CS0012 slab	Licola, Jamieson-Heyfield Road (Tiger Gully)	(D) DU 592398	9.030s	–
CS0068	Licola, Jamieson-Heyfield Road	(D) DU 616406	9.024	0.18
CS9864	Licola, Jamieson-Heyfield Road	(D) DU 592398	9.012	0.20
CS0069	Jamieson-Heyfield Road, Mt Skene	(F) DU 461549	9.024	0.21
CS0060	Eastern margin, Jamieson (Mt Sunday Tk)	(C) DU 472643	9.012	0.24
CS9845	Howqua, base of Wares Flat Tk.	(B) DU 391806	9.016	0.22
CS9848	Howqua, Steiners Tk	(B) DU 380777	9.017	0.19
CS9850	Howqua, Steiners Tk	(B) DU 368774	9.024	0.23
CS9851	Howqua, Steiners Tk	(B) DU 344774	9.030	0.24
CS9911	Howqua River, Howqua Fault, (near Wares Flat)	(B) DU 377802	9.024	0.23
CS9915	Howqua River, near Wares Flat	(B) DU 374801	9.024	0.19
CS0024	Howqua, Mitchells Tk.	(B) DU 389777	9.024	0.24

s, b_o determined from cut slab. AMG map coordinates from topographic maps: (A), Tali Karng 1:25 000, 8222-4-1/8222-1-4; (B), Buller South 1:25 000, 8123–1-S; (C), Skene North 1:25 000, 8123–2-N; (D), Licola-Wellington 1:50 000, 8222-N; (E), Buffalo 1:100 000, 8224; (F) Skene South 1:25 000 8123–2-S. S&E coordinates are latitude and longitude. See Figures 2 and 5a for localities.

GEOCHRONOLOGY

Analytical methods

$^{40}Ar/^{39}Ar$ analysis of white mica from sample CS0048 was performed at the University of Nevada, Las Vegas, following standard methods (McDougall & Harrison 1999). Samples were wrapped in tin foil and stacked in fused silica tubes with the neutron fluence monitor FC-2 (Fish Canyon Tuff sanidine). Samples were irradiated at the Ford reactor, University of Michigan, for 6 h in the L67 position. Correction factors for interfering neutron reactions on K and Ca were determined by repeated analysis of K-glass and CaF_2 fragments included in the irradiation. Measured $(^{40}Ar/^{39}Ar)r$ values were $1.56\ (\pm\ 38.21) \times 10^{-2}$. Ca correction factors were $(^{36}Ar/^{37}Ar)Ca = 2.79\ (\pm\ 6.09) \times 10^{-4}$ and $(^{39}Ar/^{37}Ar)Ca = 6.61\ (\pm\ 0.21) \times 10^{-4}$. Samples were heated using a double vacuum resistance furnace. Reactive gases were removed by two GP-50 SAES getters prior to being admitted to a MAP 215–50 mass spectrometer by expansion. Peak intensities were measured using a Balzers electron multiplier. Mass spectrometer discrimination and sensitivity was monitored by repeated analysis of atmospheric argon aliquots from an online pipette system. The sensitivity of the mass spectrometer was 6×10^{-17} mol/mV. Line blanks averaged 17.33 mV for mass 40 and 0.06 mV for mass 36.

Results

Individual flakes of mica were picked from zones of strongly aligned, fine layers of recrystallised white mica developed between rodded quartz veins in the slate, producing an almost pure separate (Figure 7b). The white mica from this black slate, from the hangingwall of the faulted western margin of the Jamieson segment, Mt Wellington Fault Zone, (Figure 5 a, b) (Skene North 1:25 000 map sheet 8123–2-N: DU434637) gives a plateau age of 419 ± 2 Ma for approximately 71% of the gas released (Figure 11; Table 3). The plateau age is probably associated with the gas from the recrystallised white mica. An age gradient from the plateau to approximately 483 Ma over the final 20% of the age spectrum suggests the presence of minor residual detrital mica within recrystallised zones. Illite crystallinity data from the Jamieson and other segments of the Mt Wellington Fault Zone indicate epizonal (greenschist) grade (IC < 0.25), which suggests the micas grew at or below their closure temperatures. The plateau age of *ca* 419 Ma is therefore interpreted to give a maximum age of fabric formation related to thrusting, as the recrystallised mica may have retained traces of minor residual older grains.

DISCUSSION

The tectonic boundary between the western and central Lachlan Orogen is defined by fault and structural zones with opposing tectonic vergence. The fault zones show similarities in terms of structural evolution, metamorphism and lithological associations, making distinction of the exact boundary difficult. The problem cannot be resolved without considering individual fault zone evolution, structural and metamorphic histories, the structures produced during structural zone collision and timing relationships, particularly before this event. Differences that have been defined in the Governor Fault Zone compared to the Mt Wellington Fault Zone include the occurrence of mélange with blocks of blueschist metavolcanics, zones of stratal disruption (broken formation), potentially slightly cooler metamorphic conditions, although these are difficult to quantify, and the occurrence of tholeiitic and boninitic ophiolitic rocks as opposed to calc-alkaline arc volcanics. More subtle differences include the slightly higher grade first foliation in pelitic rocks of the Mt Wellington Fault Zone compared to that in the mélange in the Governor Fault Zone at Howqua. The Mt Wellington Fault Zone first foliation is clearly related to tight to isoclinal folds that

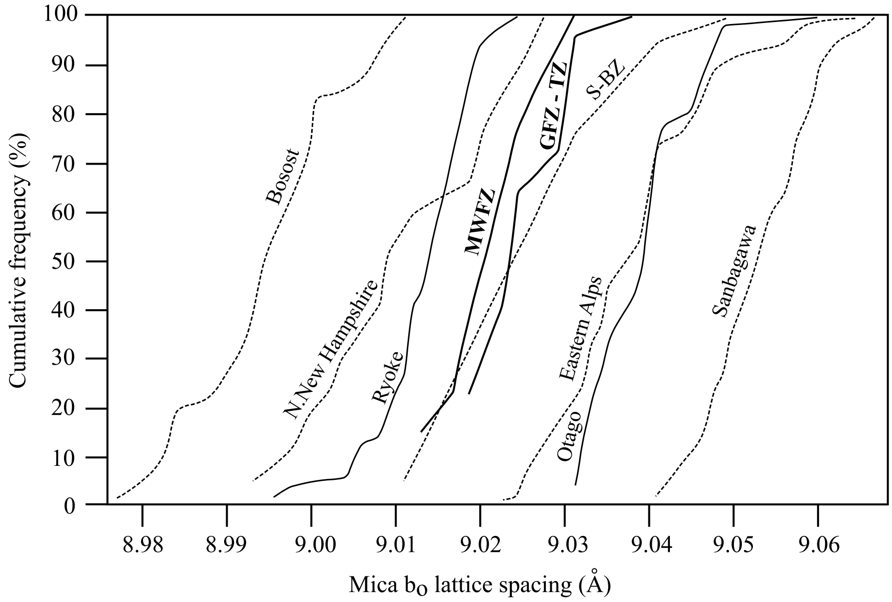


Figure 10 Cumulative percentage frequency plot of b_o data from the Tabberabbera Zone and Mt Wellington Fault Zone. The curves for Bosost (low P), N. New Hampshire (P at the Al_2SiO_5 triple point), Ryoke, Stawell–Bendigo Zones (S-BZ), Eastern Alps, Otago (intermediate P), and Sanbagawa (high P) are shown for comparison (data from Sassi & Scolari 1974; Offler *et al*. 1998). GFZ-TZ, Governor Fault Zone and Tabberabbera Zone; MWFZ, Mt Wellington Fault Zone. The data for the Mt Wellington Fault Zone and Governor Fault Zone – Tabberabbera Zone curves are given in Table 2.

most likely formed during décollement/detachment faulting, whereas the early foliation in the mélange at Howqua most likely formed during approximately layer-parallel extension and disruption (Spaggiari *et al.* 2002b, 2003b). There is also some indication that strain states were higher in the Mt Wellington Fault Zone (Gray 1995). On the larger scale, along-strike complexities documented here highlight the problem of defining the boundary as a single structure, particularly when exposure is limited to structural highs beneath unconformable cover rocks. It is therefore necessary to consider how the different segments may link up, as well as the timing relationships. The characterisation and definition of the fault zones also provides insight into the structural and tectonic evolution of the Melbourne and Tabberabbera Zones that, in turn, helps evaluate proposed tectonic models.

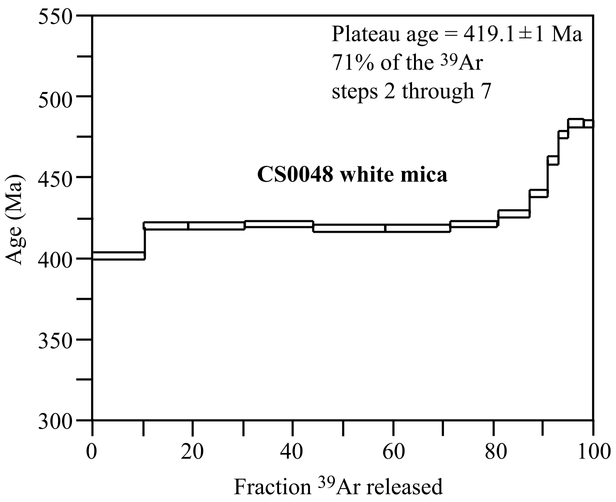


Figure 11 Ar/Ar spectrum of white mica from slate from the hangingwall of the western margin fault contact with Cambrian volcaniclastics, Jamieson segment, Mt Wellington Fault Zone (sample CS0048, see Figure 5a, b for locality; Skene North 1:25 000 map sheet 8123–2-N: DU434637). The data are given in Table 3.

Timing relationships

Suprasubduction zone magmatism and marginal basin formation occurred in the proto-Lachlan realm between approximately 505 and 495 Ma (Foster *et al.* 2002; Spaggiari *et al.* in press) with deposition of volcaniclastic debris and pelagic sediments ongoing until the Cambro–Ordovician boundary. This marked the onset of widespread turbidite deposition, denoted by the Adaminaby Group in the Tabberabbera Zone (Stewart & Fergusson 1988), which continued through Silurian and Devonian times, during deformation (Foster *et al.* 1999; Willman *et al.* 2002). The sedimentation history is, in part, problematic because much of it is dominated by sparsely fossiliferous, monotonous quartz-rich turbidites. A major change occurred just prior to the Late Ordovician (Darriwilian, *ca* 467–459 Ma) with the onset of black shale-dominated sequences (Stewart & Fergusson 1988; VandenBerg *et al.* 2000). This has been attributed to a waning in the uplift and erosion of the source area to the west (Delamerian mountains, eastern Gondwana margin) and/or a global rise in sea level (VandenBerg & Stewart 1992; Colquhoun *et al.* 1999; Fergusson & Tye 1999). More recently, Fergusson and Fanning (2002) attributed this change to the commencement of subduction in the western Lachlan Orogen, blocking sediment supply from the margin. This is coincident with early white mica growth in the western Lachlan Orogen in the basal décollement of the evolving accretionary wedge (Foster *et al.* 1999).

The onset of deformation and metamorphism in the Governor Fault Zone, East Howqua segment, is indicated by blueschist metamorphism and mélange formation at *ca* 450–445 Ma (Spaggiari *et al.* 2002b). Deformation in the Dolodrook segment appears to have occurred after this, as deposition of the Ordovician bedded chert and shale sequence had not finished until the Ordovician–Silurian boundary (marked by Bolindian fauna). In the Dolodrook segment, initial deformation probably occurred during and/or just after deposition of Lower Silurian turbidites (*ca* 440–430 Ma), during high-T/low-P metamorphism in the Wagga–Omeo complex to the northeast (*ca* 435–425 Ma), and deformation along the Wonanngatta Fault Zone (Foster

Table 3 Ar/Ar data from white mica in sample CS0048.

Step	T°(C)	%^{40}Ar*	mol ^{39}Ar	% ^{39}Ar released	^{40}Ar*/^{39}ArK	Age (Ma) ± 1σ	Ca/K
CS0048, white mica, 3.96 mg, J = 0.002008 ± 0.5%							
1	550	96.6	5.19E-15	10.3	124.1170	401.45 ± 2.08	0.017
2	580	99.7	4.47E-15	8.9	130.3939	419.56 ± 2.10	0.032
3	610	99.8	5.74E-15	11.4	130.3082	419.32 ± 2.11	0.029
4	640	99.8	6.89E-15	13.7	130.6980	420.44 ± 2.10	0.012
5	670	99.8	7.27E-15	14.4	129.8232	417.92 ± 2.09	0.014
6	700	99.8	6.45E-15	12.8	129.8246	417.93 ± 2.10	0.013
7	730	99.8	4.82E-15	9.6	130.7130	420.48 ± 2.12	0.017
8	760	99.9	3.15E-15	6.3	133.1254	427.39 ± 2.13	0.011
9	790	99.7	1.75E-15	3.5	137.7200	440.47 ± 2.21	0.017
10	830	99.9	1.17E-15	2.3	144.8807	460.68 ± 2.32	0.028
11	880	99.8	9.58E-16	1.9	150.5009	476.38 ± 2.38	0.045
12	1000	99.6	1.52E-15	3.0	153.1452	483.73 ± 2.39	0.059
13	1200	99.0	9.68E-16	1.9	153.0012	483.33 ± 2.46	0.153
14	1400	55.9	1.39E-17	0.0	85.2864	285.18 ± 9.05	3.318
Cumulative %^{39}Ar released = 100.0				Total gas age = 423.80 ± 2.11			

See Figure 5a, b for locality; Skene North 1:25 000 map sheet, 8123–2-N: DU434637.

et al. 1999; Collins & Hobbs 2001). The development of southwest-vergent folds in the Freestone Creek area (Figure 2) was most likely synchronous with similar folding in turbidites northeast and southwest of the Dolodrook segment, and was prior to Lower Devonian granitoid intrusion (Fergusson 1987).

Thrusting and duplex formation in the Mt Wellington Fault Zone is estimated to have started between 419 and 410 Ma (Foster *et al.* 1999). The maximum age of *ca* 419 Ma coincides with the end of the Silurian when deposition of the youngest rocks in the Mt Wellington Fault Zone was complete (i.e. Murderers Hill siltstone, east of the Fiddlers Green Fault: VandenBerg *et al.* 2000) (Figure 2). The Ar/Ar age of 419 Ma is from black slates that are no younger than Late Ordovician (Mt Easton Shale), and is interpreted to represent a maximum age for formation of the major structural break above the Cambrian rocks. Thrusting and associated tight to isoclinal (F1 and F2) folding took place as marine sedimentation continued during Early Devonian times (Melbourne Zone, Walhalla Group).

The main period of thrusting was followed by collision with the Tabberabbera Zone (and Governor Fault Zone) probably at approximately 400–390 Ma, coincident with what is traditionally termed the 'Tabberabberan Orogeny' (Figure 12). Major northwest-trending anticlinoria and synclinoria were most likely formed at this time (F3 folding as described here), along with continued movement or reactivation along major faults, formation of the Howqua Fault, and localised folding of major faults. Lower Devonian rocks (e.g. Walhalla Group) that occur to the west of the Mt Wellington Fault Zone in the hangingwall of the Fiddlers Green Fault (Figure 2) were also deformed at this time. Collision of the two subprovinces most likely occurred just after, or partially during, structural translation and exhumation of the Wagga–Omeo metamorphic complex (410–400 Ma: Foster *et al.* 1999; Willman *et al.* 2002). The two subprovinces were amalgamated before the Late Devonian (*ca* 380 Ma), as indicated by unconformably overlying Howitt province felsic volcanics and continental–fluvial sedimentary sequences (Figure 2) (Marsden 1976).

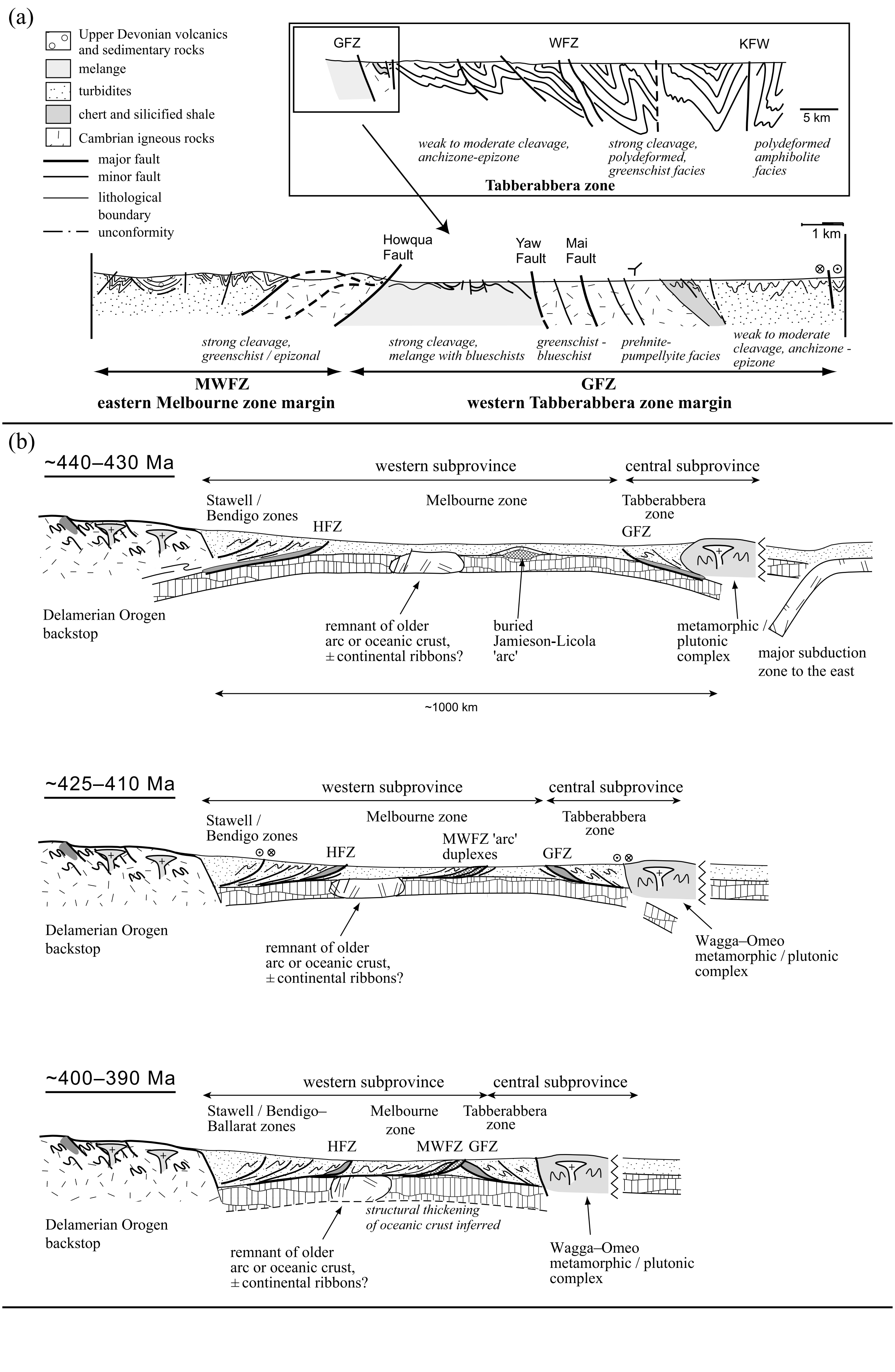
Links between Governor Fault Zone segments

Segments of the Governor Fault Zone (Dookie, Tatong, East Howqua and Dolodrook) show some differences in structural evolution, metamorphic conditions and timing of deformation that have to be considered in order to link the segments into a single fault zone and relate it to the evolution of the central Lachlan Orogen. The overall geometry of the Tabberabbera Zone has been interpreted as a leading-imbricate fan, accretionary-style thrust-wedge where the Governor Fault Zone represents the frontal part and deepest exposed levels of the system (Figures 2b, 12a) (Gray 1997; Fergusson 1998; Gray & Foster 1998). This interpretation is supported by the imbricate geometry of the Governor Fault Zone and exposure of the oceanic crust basement (Spaggiari *et al.* in press b). The Wonanngatta Fault Zone has metamorphic characteristics (average IC of 0.24, average b_o of 9.029; $n = 5$) indicative of a structural break at relatively deep levels of the imbricate system (~400 MPa, 10–12 km), and the presence of slivers of Lower Ordovician chert (Howqua Chert equivalent) in mélange in the fault zone suggests this break was in the chert horizon, possibly above Cambrian basalts similar to those at Howqua. If the Governor Fault Zone is the 'leading' part of the system, then one may expect to see uniformly developed structures along its length, but this does not appear to be the case. The along-strike differences in the Governor Fault Zone most likely relate to variable processes of disruption and deformation of the upper oceanic crust during convergence and incorporation of ophiolitic slivers into the turbidite wedge via offscraping, underplating and imbrication or duplexing (Spaggiari *et al.* 2003a, b).

Similarities in rock associations between the East Howqua and Tatong segments, although poorly defined in the latter, suggest that these two segments were perhaps continuous prior to Late Devonian basin formation. Relationships between the Tatong and Dookie segments are less clear because most of the geology is obscured by Quaternary cover and no structural link between them is evident in the aeromagnetic data. The structural evolution of the two segments is also unclear, apart from relatively late thrusting on the Dookie Fault, which most likely formed during the time the two subprovinces collided. The approximately east–west trend of this fault, and thrust relationship with weakly deformed, Silurian–Devonian rocks of the Melbourne Zone in the footwall may reflect relatively shallow-level disruption of the fault zone, and possibly localised block rotation, during potentially oblique amalgamation of the Melbourne and Tabberabbera Zones. This is consistent with observations and interpretations of interference patterns and curvilinear fold axial surface traces in the north of the Melbourne Zone (Gray & Mortimer 1996). Emplacement of the ophiolitic sequence in the Dookie segment most likely occurred well before this, perhaps at a similar time to the East Howqua segment.

Establishing a link between the East Howqua and Dolodrook segments is also not straightforward because there are clearly differences in metamorphic grade, structural evolution, lithological associations and timing relationships. It is also not clear if the Dolodrook Fault represents the boundary between the Melbourne and Tabberabbera Zones given that the turbidite succession southwest of the fault is weakly deformed, and clearly not part of the Mt Wellington Fault Zone. These turbidites have both sedimentological and structural affinities with turbidites in the Tabberabbera Zone to the southeast in the Freestone Creek area (Figure 2) (Cobbannah Group as described by Fergusson 1998; Fergusson & Tye 1999; Spaggiari *et al.* 2003a). This suggests that the Dolodrook segment may be within the Tabberabbera Zone, and not necessarily the site of collision of the Melbourne and Tabberabbera Zones.

Figure 12 (a) Schematic composite profile across the Mt Wellington (MWFZ) and Governor Fault Zones (GFZ) showing interpreted geometry of the Jamieson and Howqua segments. Inset shows a profile of the Tabberabbera Zone, with the Governor Fault Zone as the western margin (modified from Fergusson 1998; Watson & Gray 2001). (b) Tectonic sketches illustrating the main period of backarc basin closure, and Melbourne Zone and Tabberabbera Zone collision, from *ca* 440 Ma (Early Silurian) to 390 Ma (Middle Devonian), modified from Foster and Gray (2000).



(a)
Upper Devonian volcanics and sedimentary rocks
melange
turbidites
chert and silicified shale
Cambrian igneous rocks
major fault
minor fault
lithological boundary
unconformity
GFZ
WFZ
KFW
5 km
weak to moderate cleavage, anchizone-epizone
strong cleavage, polydeformed, greenschist facies
polydeformed amphibolite facies
Tabberabbera zone
1 km
Howqua Fault
Yaw Fault
Mai Fault
strong cleavage, greenschist / epizonal
strong cleavage, melange with blueschists
greenschist - blueschist
prehnite-pumpellyite facies
weak to moderate cleavage, anchizone - epizone
MWFZ
eastern Melbourne zone margin
GFZ
western Tabberabbera zone margin
(b)
~440–430 Ma
western subprovince
central subprovince
Stawell / Bendigo zones
HFZ
Melbourne zone
Tabberabbera zone
GFZ
Delamerian Orogen backstop
remnant of older arc or oceanic crust, ± continental ribbons?
buried Jamieson-Licola 'arc'
metamorphic / plutonic complex
major subduction zone to the east
~1000 km
~425–410 Ma
western subprovince
central subprovince
Stawell / Bendigo zones
Melbourne zone
HFZ
MWFZ 'arc' duplexes
Tabberabbera zone
GFZ
Delamerian Orogen backstop
remnant of older arc or oceanic crust, ± continental ribbons?
Wagga–Omeo metamorphic / plutonic complex
~400–390 Ma
western subprovince
central subprovince
Stawell / Bendigo–Ballarat zones
Melbourne zone
Tabberabbera zone
HFZ
MWFZ
GFZ
structural thickening of oceanic crust inferred
Delamerian Orogen backstop
remnant of older arc or oceanic crust, ± continental ribbons?
Wagga–Omeo metamorphic / plutonic complex

That boundary is possibly further to the southwest, perhaps even obscured by the Barkly Fault near Licola. If this is the case, then it is questionable as to whether the Dolodrook segment should be defined as part of the Governor Fault Zone. In the East Howqua segment, mélange forms the frontal part of the Governor Fault Zone, but is overridden by the Mt Wellington Fault Zone with the Howqua Fault at its base. Therefore, it is unclear whether the front of the Tabberabbera imbricate-fan system is what is exposed there as it may be buried further west. In short, the Governor Fault may not actually be exposed in any of the segments if it is defined as the basal fault of the Governor Fault Zone.

Differences in structural and metamorphic evolution provide another means of interpreting the nature of the tectonic boundary. The Ordovician rocks in the Dolodrook segment do not share the same deformational characteristics as those in the mélange zone at Howqua. In particular, they do not have well-developed crenulation cleavages nor marked fabric development due to pressure solution, and recrystallisation of white mica is rare. There is also no indication of high strain, such as rodding in quartz veins or development of pressure shadows. Tight to isoclinal folding may have taken place in only partially lithified rocks and is therefore not indicative of ductile deformation in the usual sense. The differences in metamorphism and deformation probably relate to differences in structural level within the turbidite wedge, with the mélange at Howqua representative of the most deeply buried rocks in the fault zone, and the serpentinite body and associated rocks at Dolodrook, which may have been an oceanic high such as a transform fault zone or seamount, representative of shallower levels that were never deeply buried by faulting. The Dolodrook segment may also have been inboard (southwest, present coordinates) of the East Howqua segment, and therefore deformed slightly later as the turbidite wedge migrated to the southwest. This probably occurred after mélange formation (East Howqua segment), and during imbrication and uplift of the turbidite wedge. Forward propagation of the wedge may then have transported the segments into an apparent, along-strike linearity (Spaggiari *et al*. 2003b).

Subprovince collision

The amalgamation of the Tabberabbera Zone (Governor Fault Zone) and the Melbourne Zone (Mt Wellington Fault Zone) represents formation of the western and central Lachlan Orogen boundary. This boundary is exposed at Howqua as the Howqua Fault and at Dookie as the Dookie Fault. In the Howqua region, subprovince collision led to thrusting of the Mt Wellington Fault Zone over the Governor Fault Zone, followed by open folding along northwest-trending axes in both fault zones (Figures 5, 6, 8). These folds are inclined to the southwest in the Mt Wellington Fault Zone, which may reflect continued overriding of the zone to the northeast. The collision produced minor backthrusting in the Governor Fault Zone, indicated by top to the northeast slickensides in pillow basalts and inferred steepening of fold axes and offsets along contacts in the chert and turbidite sections (cf. profiles in Fergusson 1998). Minor strike-slip adjustments may also have occurred on major faults (e.g. Yaw Fault) at this time, as indicated by small apparent offsets in aeromagnetic imagery (Spaggiari 2002, 2003a).

The Mt Wellington Fault Zone and Governor Fault Zone are only exposed adjacent to one another in the Howqua region (Figures 2, 5a, 12a). Fold and fault orientations there suggest consistent northeast transport of the Mt Wellington Fault Zone and southwest transport of the Governor Fault Zone. There is no obliquity in fold orientations that stitch the fault zones, but it is not known whether these relate directly to structural zone collision or if they formed sometime afterwards as they also fold the Howqua Fault. It is also not clear whether these structures are indicative of collision orientation at a larger scale. Tectonic vergence, as determined by fault dip direction and fold inclination (Gray 1997), provides some insight and indicates southwest transport of the Tabberabbera Zone, and east or northeast transport of the Melbourne Zone. The collision may also have involved an element of block rotation, which may account for strike-slip displacements on some faults. High magnetic signatures in aeromagnetic data northwest of the Dookie segment suggest the Governor Fault Zone curves to a more easterly trend where it apparently truncates the Heathcote Fault Zone. This suggests a component of southeast or south transport, probably late in the history of the Governor Fault Zone as it truncates major bounding faults of the Heathcote Fault Zone that clearly underwent reactivation in at least post-Early Devonian times (Spaggiari *et al*. 2003b). This possibly also explains the anomalous east–west trend of the Dookie Fault.

Late Devonian basin formation appears to have had little effect on the underlying fault zones, although their formation is not well understood. Rocks within the basins are only weakly deformed, unmetamorphosed and show virtually no cleavage development, consistent with deformation at very shallow crustal levels. The latest deformation to have affected the Mt Wellington Fault Zone, apart from small-scale reactivation, is recorded by northeast-trending kinks and warping, particularly in the Jamieson segment. These probably relate to Late Devonian basin formation or folding during fault reactivation in the Mt Wellington Fault Zone during the Early Carboniferous.

Implications for tectonic models

Interpretations of Mt Wellington Fault Zone and Governor Fault Zone evolution, and what they represent in terms of respective structural zone evolution, have implications for tectonic models of Lachlan Orogen evolution. Any proposed tectonic model must account for the structural geometry and kinematic evolution, the presence of ophiolites, the occurrence of Late Ordovician blueschists in mélange, timing relationships and the turbidite-dominated, predominantly oceanic setting. Some models propose that the boundary represents a major strike-slip zone (Glen 1992; Willman *et al*. 2002). Intraplate, thin-skinned thrusting inboard of a distant, west-dipping subduction zone has also been proposed but this does not account for the differences in tectonic vergence (Fergusson 1987). That problem is overcome by a model of double-divergent subduction, also inboard of a major subduction zone to the east (Gray 1997; Gray & Foster 1998; Foster *et al.* 1999; Fergusson & Fanning 2002). The observations and interpretations outlined here support a model of multiple subduction zones where the inboard subduction zones relate to closure of a backarc or marginal basin (Figure 12b). They are interpreted to have formed by underthrusting of the oceanic crust during convergence, perhaps on a relatively small scale in comparison to the inferred eastern subduction zone (Gray & Foster 1998; Foster *et al.* 1999; Spaggiari *et al.* 2002a, 2003b).

Willman *et al.* (2002) proposed a model suggesting lateral wholesale translation of the western Lachlan Orogen along the western and central Lachlan Orogen boundary (and eastern Selwyn Block margin), with estimated displacement in the order of 600 km. They suggest the central and eastern subprovinces (Figure 1) represent duplication of the western subprovince, based on correlation of Ordovician–Silurian stratigraphies. Strike-slip translation is inferred to have taken place from approximately Middle Silurian (*ca* 420 Ma) to Early Devonian times along an inferred major fault (Baragwanath transform) along the eastern margin of the Melbourne Zone. That fault is inferred to have been overprinted by southwest-directed thrusting along the 'Governor Fault'. Early structures, geometrical relationships and metamorphic patterns in the Mt Wellington Fault Zone and Governor Fault Zone (Spaggiari *et al.* 2002a, 2003b) are indicative of thrusting and duplex formation, and are overprinted by strike-slip faults that mostly appear to have only minor displacement. These observations are at odds with the proposed strike-slip model in its current form. Within the fault zones, there is little, if any, evidence for systematic development of oblique, steeply plunging folds, curvature of the main foliation into the fault plane, subhorizontal mineral lineations or fault jogs as might be expected in a wrench system. Instead, mineral and stretching lineations are all approximately downdip and, where developed, kinematic indicators are indicative of thrusting. Furthermore, Ar/Ar dating of mélange and main fabric formation in the East Howqua segment (*ca* 445 Ma: Spaggiari *et al.* 2002b) shows that the Governor Fault Zone formation was well underway prior to and during the inferred time of Baragwanath transform motion, and was not a 'late, overprinting' thrusting event.

The structural and metamorphic evolution of the Mt Wellington Fault Zone is also at odds with the proposed Selwyn Block, particularly in terms of its eastern margin, which is inferred to lie just east of the Governor Fault Zone (Cayley *et al.* 2002). The structural data presented here indicate synchronous deformation of the Cambrian volcanic succession with pelitic cover rocks, and no foliation discordance as suggested by Cayley *et al.* (2002), inferred to be representative of an earlier, 'Delamerian age' deformational event. Furthermore, these foliations are well developed and of lower greenschist metamorphic grade (Figure 7a, c), which is difficult to account for purely by overthrusting of the cover sequence over the upper portion of a continental margin arc (see also VandenBerg *et al.* 1995). The formation of the Mt Wellington Fault Zone is interpreted to relate to the relatively late stages of marginal-basin closure, following reactivation of major faults to the west such as the Heathcote Fault Zone (Foster *et al.* 1999), and involving disruption and thrusting of the basal Cambrian oceanic/arc crust (Gray & Foster 1998; Spaggiari *et al.* in press b). Slightly higher metamorphic grades in early fabrics of the Mt Wellington Fault Zone compared to the Governor Fault Zone may be indicative of a slightly higher geothermal gradient by approximately 420–410 Ma, which culminated with intrusions of Middle to Late Devonian relatively primitive granitoids and dykes following basin closure and subprovince collision (Soesoo *et al.* 1998; Bierlein *et al.* 2001). The suggestion of continental crust beneath the Melbourne Zone is partly based on interpretation of aeromagnetic data across Bass Strait (Figure 1) (Cayley *et al.* 2002), but these data have poor resolution and are difficult to trace onshore both on the mainland and into Tasmania where there is greater resolution. It is not unreasonable to expect remnants of older oceanic or arc crust, or slivers of relict rifted continental margin crust to be preserved in what was initially a suprasubduction zone setting, but more substantial evidence is required to constrain this.

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